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PROCEEDINGS

FIRST MEETING, FIRST HALF, 64TH SESSION

In the Chair : THE PRESIDENT, COLONEL THE MASTER OF SEMPILL

THE TECHNICAL DEVELOPMENT OF THE AEROPLANE

BY

JOHN D. NORTH, Fellow and Member.

The first meeting of the 1928-29 Session of the Royal Aeronautical Society was held in the rooms of the Royal Society of Arts, John Street, Adelphi, London, W.C.2, on Thursday, October 4th, 1928.

The PRESIDENT: Mr. North is one of the foremost designers in the country. Since early in 1911 he had devoted his activities exclusively to aeronautics and for many years had been responsible for the design of all aircraft produced by Boulton and Paul, of Norwich.

Mr. North had been very intimately connected with the design of the Government airship now in an advanced stage of construction at Cardington. His great experience of light steel structures had been utilised to the full in this connection.

Mr. J. D. NORTH: The technical development of the aeroplane falls under two heads; (1) development for the purpose of obtaining better results than those yielded by present standard good practice; (2) perfection of technique so that a designer's expectations may be realised with certainty and that results not worse than standard good practice may be assured. There is a gap between research and our scientific knowledge resulting therefrom on the one hand, and the creative process of design on the other; the attempt to bridge this gap is commonly called technique. The number and complexity of the variables involved render a truly logical process of design out of the question. The subconscious mind of the designer will suggest solutions to the problems put before it, and those solutions must be verified and refined by technique.

It is, perhaps, unfortunate that flying machines can be produced in extreme forms; so much so that, in the early days, we saw actually flying aeroplanes in the form of annuli, hollow rhomboids and other grotesque geometrical shapes. The inspirations of designers to-day seldom take such extravagant forms and, while it is undesirable to pour cold water on unusual designs merely because they are strange, rigorous technical analysis is equally desirable to exclude mere novelities, as distinct from improvements.

It will be understood that much of the work classed as technical development to-day consists in the production of new general arrangements incorporating new engines or new equipment and that this is distinct from the essential continuity of effort necessary to make real technical advances.

The vortex theory of aerofoils and airscrews is a striking example of improvement in technique. It has brought into proper perspective the huge mass of wind channel results which was formerly the designer's source of information for the design of his lifting surfaces. At the same time it has indicated the limitations of aerofoil sections, plan forms, décalage and the like.

It is fair to say that, within limitations, an aerofoil section can be designed to have specified properties with considerable certainty. $dk_L/d\alpha$, km_o, dk_m/dk_L and the k_L corresponding to minimum profile drag are probably calculable for an elliptic plan form to a higher degree of accuracy than they can be measured in the wind channel and, even for rectangular plan forms, serious disagreement between the results of wind channel tests and calculation must throw suspicion on the former. A symmetrical streamline section capable of containing the wing structure can be found and the desirable characteristics obtained by appropriate curvature of the centre line. Profile drag and kl_{max} can be estimated with a good order of accuracy; the wind channel determination is difficult, since one is a residual quantity and both are subject to large scale effects. There are even greater experimental difficulties in their actual full scale measurement. Induced drag on rectangular monoplane and multiplane arrangements with uniform section can be calculated with a degree of accuracy somewhat surprising in view of some of the evidence relating to pressure distribution.*

As the designer has to arrange his aerofoil section to contain his wing structure, it is natural that, for a given span, reduction in chord should tend to lead to increased thickness of the aerofoil. Except in the cases of aeroplanes designed to operate at very high indicated air speeds only, an aeroplane for which 50 miles per hour is an acceptable stalling speed can derive practically no gain in top speed or climb by the use of a wing section having a maximum lift coefficient greater than .7; the increase in thickness due to further chord reduction causes the profile drag to remain substantially constant, while the structure suffers a definite disadvantage owing to the closing in of the spar centres. For this reason there is little improvement to be expected in aerofoil performance, even by the use of slots.

In the case of wings in which the form or dimensions of the aerofoil vary along the chord there is no such good agreement between measurement and calculation. The writer has observed from wind channel experiments† lift/drag ratios considerably inferior to calculation with certain methods of tapering. Other wind channel tests reveal no evidence of such discrepancies; but caution seems to be indicated in the design of wings of this class. It is worth while pointing out that aerodynamically affine wing sections should have a uniform curvature of the centre line. If affine sections are produced by mere changes of horizontal and vertical scale, the characteristics of the section fundamentally alter.

The design of an efficient streamline body of low resistance for a given area or volume is not difficult, and forms may be generated mathematically‡ or graphically.§ Airship forms of $5\frac{1}{2}$ to 1 fineness have reached the low figure of .39lbs. per sq. foot at 100 feet per second for Vl 285. Such low resistance

* *Cf.* N.A.C.A. Report No. 288, 1928.

† Unpublished.

‡ v. "Two-dimensional Aerofoil Theory," by Muriel Glauert, *Aeronautical Journal*, XXVII., July, 1923.

§ See App. I., "Some Modern Developments in Rigid Airship Construction," by Richmond, Inst. N.A. Session 69, Paper 9.

forms are seldom possible, owing to the greater fineness ratios necessary in aeroplane construction. If the fineness ratios of bodies, not solids of revolution be expressed as $\pi \times$ length/max. periphery without excrescences, characteristic fineness ratios are as follows: but it must be remembered that for structural reasons a properly generated streamline form may have to be truncated at the tail. This means that the effective fineness ratio is really much greater as, for example, for aeroplane D, the fineness ratio would be 8.61, and not 6.66, if it were not for this truncation.

A.	Racing Aeroplane	6.49
B.	Single-Seater Fighter, air-cooled engine	5.21
C.	,, ,, water-cooled engine	6.09
D.	Twin-engine Day Bomber	6.66
E.	Night Bomber	8.56
F.	Commercial Three-engine Transport	8.17

It is, of course, useless to obtain low coefficients of resistance by counterbalancing increases of area, but with experience it is possible to generate basic streamline shapes to include the equipment and internal arrangements desired from operational and structural considerations with a minimum of area. This shape can be modified little by little to the ultimate form, ensuring that the additional drag due to breaks in the streamline form shall be kept as low as possible. In Appendix I. the development of a body by these means is outlined in detail, and a comparison given with an older type of body designed for similar purposes. The new design has reduced the drag by 30 per cent.

A body and wing tested and found satisfactory as independent units may, in combination, give poor results. Appendix II. gives wind channel figures showing the effect of mounting a monoplane wing on a body. Interference drag, without loss of lift, is shown increasing with incidence; the influence of the relative attitude of wing and body is notable. In Appendix III. is shown the effect of varying the amount of cutaway in the top wing of a biplane combination and the reduction of interference drag obtained.

In Appendix IV. similar results for a combination of body and bottom wing are given. The striking feature of these results is the large magnitude of the interference drags and the fact that by systematic wind channel tests they have been, if not eliminated, at least relegated to a part of the flight range where they can do a minimum of harm; that is, below what would be the best climbing speed if interference were totally absent. Some adverse effect on climb, of course, remains near the ceiling, where this condition can hardly be satisfied.

These tests have been selected as illustrations, and it is not suggested that the remedies for interference found in these cases can be of general application; on the contrary, the eye is an uncertain guide, and wind channel tests of any combination may be necessary to ensure absence of interference, although empirical knowledge is of great assistance in obtaining a quick solution.

In the types of interference just discussed there has been only a small effect on lift, even where interference has increased with incidence. Appendix V. gives results for twin nacelles, both between the wings and mounted on the bottom wing. There interference drag rises rapidly with incidence and heavy losses of lift are shown. The tests show that the effect on the bottom plane is most marked and is reduced by the presence of the top plane. This effect of the apparent reduction of bottom plane interference by the presence of the top wing is quite common. These interferences can also be confined to speeds outside the ordinary flight range, or otherwise so reduced as to have a comparatively small effect on performance; but here again there seem to be no rules of design which will avoid the necessity for wind channel tests.

This type of interference, if present, has very serious effects on performance, and appears to be due to increase of induced drag consequent on the disturbance

of the lift distribution over the wing. The question of induced interference, here, I believe, put forward for the first time, is one of first class importance, and it would be of interest to have pressure distributions for characteristic interferences of this class.

The conjunctions of struts and aerofoils give rise to interferences, even when the struts fit close to the wing without discontinuities introduced by fittings. Some figures for a single strut at different angles to the wing and for different angles of incidence are given in Appendix VI. Apart from their bearing on the liability of strut-wing interference, these wind channel results suggest that tests for fittings mounted on planes must be made under representative conditions of lift, and not on flat plates at zero lift.

All these statistics, which have been selected as examples only from a considerable mass of results, of most of which there is adequate qualitative full scale confirmation, indicate some of the pitfalls in the path of the aeroplane designer. The wind channel provides a slow and fairly sure means of avoiding them, but the technique of the work is difficult, particularly in small channels. Misleading test results may arise from two causes in particular,

(1) Insufficiently representative models.

(2) Scale effect.

Probably more models fail from imperfect representation than from any other cause, and within the limits of a small wind channel (*e.g.*, 7ft.) scale effect difficulties limit accuracy and completeness of representation.

Since the criterion of scale, Vl/ν, contains the dimension of length, the exposed parts of a radial engine model, for example, may well be subject to an unrepresentative flow, although the wing chord of the model is at a satisfactorily high Reynolds number. A similar difficulty is experienced in representing exposed struts, wires and fittings upon models. The flow round a streamline strut cannot be considered reasonably representative at a value of Vl less than 3.5. This generally means that, for a velocity of 60 feet per second, a $\frac{1}{4}$ scale model would be necessary if the struts were to be included. The representation of wires and small fittings would be useless, even on $\frac{1}{4}$ scale. If the flow round a strut or other exposed part is not representative, the interference resulting from the conjunction of this part with the wings or body is consequently misleading. A 1/12 scale model of, say, a seaplane, with its fairly complicated chassis constructed with true-to-scale struts, would have the performance of the model entirely masked by the abnormal resistance and interference of these struts. We at Norwich have endeavoured in a measure to overcome this difficulty by constructing partial $\frac{1}{4}$ scale models and determining their aerodynamical properties in the presence of representative interferences. We then reproduce these parts on smaller scale and more complete models so that the correct aerodynamical characteristics for the higher scale are present, even if geometrical similarity has to be disregarded. Such a procedure necessarily contains elements of uncertainty but, although it is often very tedious, it represents, I believe, the only safe method of procedure in comparatively small channels. The use of a variable density channel of a size apparently rendered practicable from considerations of cost hardly gets over the difficulty, since the model is too small to be accurate in detail.

The evidence of the effect which interference has on performance is so extensive that the technique of design must be sufficiently strong to enable the designer to feel confident that his machine will not fail in performance from this cause. It is difficult to find time to carry out all the wind channel tests, which, with our present knowledge, seem necessary.

The effects of interference, more particularly induced interference, are most noticeable on climb, and it is interesting to note in this connection that the early

so-called " full scale characteristics " of R.A.F. 15 showed a discrepancy in the values of the drag coefficient at the higher values of the lift coefficient as compared with the model tests, which, in the light of present knowledge, must be attributed to induced interference on the aeroplane, and which at that time was included as a property of the wing section. It is notorious that aeroplanes fail in performance more frequently on climb and ceiling than on speed, because it is in these directions that induced interference has its most marked effect. That class of aeroplane which is designed primarily to obtain a high horizontal speed is an easier design proposition than the aeroplane which has to give a good performance at a high lift coefficient. Similarly, the more operational requirements force a departure from simple aerodynamic forms, the more difficult it is to avoid interference.

It must be remembered also that change in drag has a comparatively small effect on speed. A 10 per cent reduction in the total drag of an aeroplane at top speed at ground level will, on an aeroplane with a big speed range, only make a difference of about $3\frac{1}{3}$ per cent. on top speed. This amount is outside the experimental accuracy of routine testing. It is not to be thought on this account that small changes in drag are unimportant, any more than small changes in weight are negligible. The oft repeated fallacy that changes in weight which are of the order of magnitude of the difference between two pilots can be of no importance is an error of logic, as much as an error in aeronautical engineering, which still sometimes requires to be exposed.

I think that if it were possible to institute a series of comparisons of routine testing at various stations, in the same way as international wind channels have been compared, we should find that 5 per cent. variations were not uncommon. Although the international wind channel trials have shown considerable discrepancies, particularly in the measurement of the drag of streamline bodies, the comparative accuracy of work in individual wind channels may be much higher. Those working in aerodynamical laboratories may take heart from the study of comparative results obtained by reputable analytical laboratories on the carbon determination for the same steels. To what extent the full scale routine testing of individual stations can be considered reliable there is some doubt, but from the evidence which I have seen I should hesitate to place the accuracy higher than plus or minus $2\frac{1}{2}$ per cent.

We may now turn to the question of improvement in aerodynamical efficiency, and in this connection I should like to draw attention to a very significant paper by Professor B. M. Jones which has been published under the auspices of the Aeronautical Research Committee as R. & M. 1115. In this paper Professor Jones contrasts performances which are obtained by present-day aircraft with those which would be obtained on the assumption that resistance due to turbulence was wholly eliminated. He suggests that a value of $k_F=0.0017$ for a Reynolds number of 10^7 should be a liberal estimate for determination of the skin friction. This corresponds to a frictional coefficient of .003 for *Vl* 30. It is, I think, open to some question whether the apparent frictional coefficient on streamline bodies decreases in the same way as the coefficient for a flat plate or, in other words, whether a wing section or streamline body which has an apparent skin friction coefficient less than the flat plate coefficient at a given value of the Reynolds number will necessarily still have a less value when the Reynolds number is higher. That great caution must be exercised in coming to a definite conclusion in this direction can be seen by considering the variations of profile drag coefficients from tests in the variable density channel at Langley Field. Some selected curves illustrating these are given in Appendix VII. From these it would appear that a steady reduction of profile drag or a violent change in profile drag with Reynolds number may be expected in the region of $k_L=0$; but it is notable that at high values of k_L the profile drag coefficient is actually rising when Reynolds

number increases above a certain value. The figures which Professor Jones gives in his paper for the frictional coefficients on streamline bodies, particularly those deduced from the international trials, can hardly be said to support the view that the apparent frictional coefficient gets smaller as the Reynolds number increases. If the results of the variable density channel are to be believed—and there is, after all, at the present moment no other experimental evidence of flow at high Reynolds numbers to which we can attach greater confidence—it would seem that there is some important work to do in obtaining further evidence as to the full scale performance of streamline bodies. I would suggest that some useful information might be obtained by towing gas-filled streamline envelopes behind large airships, in order to provide a check on the work of the variable density channel and, at the same time, afford us a better understanding of the significance of wind channel work at atmospheric pressures.

My reason, however, for drawing attention to Professor Jones' paper is its great value in emphasising the tremendous losses in turbulence on what we today consider a good aeroplane. In order to amplify this point of view, I have had prepared an analysis* of three typical aeroplanes of good performance, for the purpose of illustrating where these losses in aerodynamical efficiency occur. From the total resistance of the aeroplane has been deducted the induced drag and the induced interference drag, if any. The balance has been split up into percentages without slipstream effect, and the tables repeated again with characteristic slipstream values for top speed and climb. Although these aeroplanes are of widely different types, they show a reasonable uniformity in the analysis, taking into consideration the variations in surface loading and power loading. The effect of the geared engine on the slipstream factor, which is indicated by the comparative values for R/R_o, rather under-estimates the advantage of the geared engine which, on the multi-engine aeroplane, cannot be fitted with quite the best diameter of airscrew, from other considerations. On the single engine aeroplane we should expect to find an even more marked advantage from the use of the slow running propeller.

First in order of importance is the resistance due to the engines. We seem to make little improvement in this direction.† Professor Jones has pointed out how wasteful is the method of cooling by honeycomb radiators or by freely exposed fins on the cylinders, both of which set up turbulence losses. These losses are notably high as compared with the frictional losses with which the cooling must necessarily be associated. These disturbances, again, are almost inevitably placed on a part of the body where they do the greatest damage to the streamline flow and they are augmented by the full effect of the slipstream.

So far it has been found possible to use on racing aeroplanes types of radiators conforming to the surface of the aerofoil (similar, incidentally, to those used by Santos Dumont over twenty years ago) and the use of these radiators reduces the resistance of the engine cooling to an almost negligible quantity. Unfortunately such radiators are liable to give rise to trouble in service and they have serious military disadvantages owing to the enormous area exposed to damage by enemy fire; it is difficult to control the engine temperature satisfactorily and to keep down the waterways so as to avoid carrying heavy weights of water. A partial solution to these problems is obtained by using a withdrawable honeycomb radiator to provide the amount of additional cooling, over and above that for ordinary cruising, necessary for climb or in exceptionally hot weather conditions.

The revival of another twenty year old aeronautical device in the form of evaporative cooling offers prospective advantages in connection with surface radiators, since it is automatic with regard to temperature control and

* Appendix VIII.

† *Cf.* tables given in Appendix A, "Technical Development of the Aeroplane," by J. D. North, Int. Air Congress, London, 1923.

obviates the difficulty with regard to size of waterways. It seems probable that nothing but technical difficulties stand in the way of the general use of such a means of cooling engines with jacketed cylinders, and that these difficulties are not insurmountable. As they involve engine problems as well as aeroplane problems, it seems that the attack on these difficulties should be made independently of the construction of experimental aircraft. Once a satisfactory system has been evolved, there will be no difficulty in incorporating it.

The problem of cooling engines by direct contact with the air in a more economical manner than at present is one of greater and more fundamental difficulty. As Professor Jones properly points out, the solution to the problem may come rather from the work of the physicist who makes a new attack on the problem than from that of the engineer who endeavours to find palliatives in the form of helmets and other types of fairing. The radial air-cooled engine has reached a remarkably high state of mechanical perfection, nowhere more so than in this country. If we can add to the simplicity of the manufacture and maintenance of these engines the low resistance of the surface-cooled engine which depends on water or water vapour as the cooling vehicle, we shall have made a wonderful advance.

We have in air cooling the special advantage that the temperature difference between the cooling surface and the air is a great deal higher than in water or steam cooling. At the same time the temperature gradient in the air surrounding the air-cooled cylinder is very steep. If we could obtain a streamline flow over the cooling surfaces with an arrangement of cylinders in line or V, we might be prepared to use some additional mechanical means of promoting the circulation of the air around the cooling surfaces. Unfortunately, the production of every new engine is attended by a host of technical difficulties and the road to progress is likely to be a hard one.

It is as well to consider in looking at these tables that, to get a proper perspective of the effect which the engine resistance has upon the design of the aeroplane, it is almost necessary to add together the items grouped under body and engines. It will be seen then that on all three types the percentage contribution of the engine group towards drag is of the same order. An endeavour has been made to put a particular figure on the direct cooling resistance by taking the drag of the bodies or nacelles with and without the presence of the exposed cylinders, but it must be remembered that the body or nacelle is not as low in drag as it would be if it were not designed to have the cylinders projecting from it.

The next substantial item is the undercarriage. If we are to eliminate the resistance of the undercarriage, I think we are more likely to be able to do so by abolishing altogether the undercarriage as at present understood than by making attempts to fold it within the body. Even were it possible to overcome, with reasonable weight and economy, the mechanical difficulties of such a device, the increased size of body necessary would add almost as much resistance as the retraction of the undercarriage would save. In the case of aircraft which are intended to be operated from particular stations it is, I think, not impossible to consider the abolition of the undercarriage in its present form. Twenty-five years ago aeroplanes were launched by means of a mechanical device. In the special circumstances of aircraft carried on marine ships they are still launched mechanically, and it should not be too difficult a problem to launch them once again from the ground to-day. The problem of making an aeroplane, so launched, able to land in safety with a landing gear which in flight would offer practically no resistance could, in my opinion, be solved.

The body, which fulfils the function of transmitting the forces from the stabilising and directing organs to the main wing structure as well as containing the load to be carried, can be made to reach a high standard of aerodynamical

efficiency by the maintenance of a simple streamline form. The building up of a body with excrescences as economically arranged as we know how has been described, and such a body, even in relation to a good streamline form, is not too poor. If we consider the measure of efficiency of the basic shape of the body as being the ratio of its apparent frictional coefficient to the flat plate frictional coefficient for the appropriate Reynolds number, then the efficiency figure of such a body is of the order of 1.1 to 1.3. Even when the excrescences are added the efficiency figure only falls to about .7. There is something to be gained here, but not so much.

Of the remaining items, it is as well to remember in considering the resistance of the empennage that there is an induced drag on the tail to be added to the figures tabulated, although there may be some regenerative action due to the downwash from the main planes. The interference figures between struts and planes which we have previously discussed may be capable of reduction, but it is probable that in a wing constructed without external bracing as much is lost on profile drag as is saved by eliminating the struts and wires. It is significant that the world's fastest aeroplanes are externally braced structures.

Very little time is left to deal with the structural side of the problem. As for the main planes, there is a conflict between induced drag, on the one hand, and the weight of the wings, which rises rapidly with increase of span, on the other. Boulton & Paul, Limited, have recently been carrying out investigations on behalf of the Aeronautical Research Committee into the influence of wing span on the weight of wings, and no doubt the result of these will shortly be available.

Technically speaking, metal construction has realised all the structural economies expected of it. It is, perhaps, unfortunate that operational requirements have to some extent masked these advanages if we think in terms of gross structure weight and, at the same time, on sound economic grounds, some of the potential saving in weight has been exchanged for reduction in induced drag. It is possible to imagine a parallel of Professor Jones' analysis of the aerodynamical efficiency of aeroplanes in the form of an investigation into what the structure of an aeroplane would be as a flying machine only, compared with what it is when arranged to satisfy numerous operational requirements. The results, I believe, would be no less striking.

The influence of scale on the economics of the aeroplane is of first class importance. As we are to have the pleasure of a paper on this subject later in the session, it is not necessary to discuss it at length. Those parts of the aeroplane whose strength requirements are due to air forces follow the usual structural laws of scale. Much of the weight is related to the physical characteristics of human beings—seating, controls, parachutes, oxygen—and extensions of human faculties, such as wireless and camera. Preponderance here tends to increase the economic size.

I have devoted considerable space to dealing with those aspects of aeroplane design in which there lie potential troubles and difficulties for the aeronautical engineer. These stand in the way of advance. We do not necessarily need new fundamental discoveries to make progress. Every year we see new athletic records broken, and this is not due to improvement in human physiology, but to improvement in technique. The development of aeronautical technique is disproportionately expensive to its present market value. Given the determination to make definite progress and the means to carry it on free from difficulties not technically inherent, aeronautical engineering is capable of moving forward more rapidly than it has done in the last decade.

The writer gratefully acknowledges the assistance received in preparing this paper from various members of the experimental staff of Boulton & Paul, Ltd., in particular A. G. Odgers, M.A., D.Sc., and J. L. Hutchinson, B.A. Except where stated to the contrary, all the wind channel results are from tests carried out

by Messrs. Boulton & Paul, Ltd., Norwich. The Blackburn Aeroplane & Motor Co., Ltd., kindly gave permission for the publication of the matter in Appendix IV., which was abstracted from work carried out at Norwich on their behalf.

APPENDIX I.

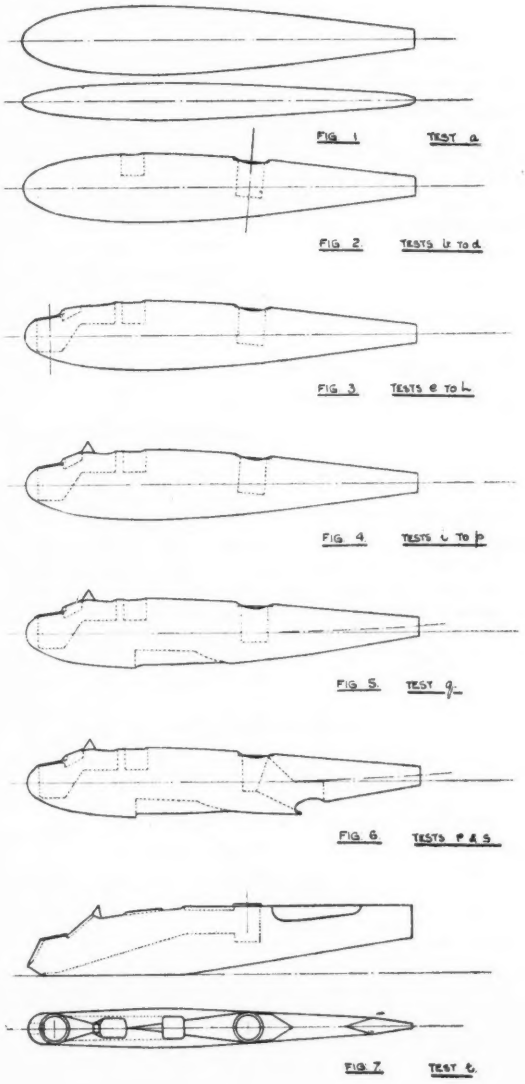


Fig.	Test No.	Model Tested.
1	*a*	Basic shape.
2	*b*	Modified nose shape; rear cockpit cut in fuselage.
	c	Gun ring added to rear cockpit.
	d	Navigator's cockpit added; gun ring removed.
3	*e*	Pilot's cockpit added; no gun rings.
	f	Nose gunner's cockpit and gun platform added.
	g	Gun platform faired to body.
	h	Gun ring added.
4	*i*	Wind screen and decking to pilot's cockpit added.
		Front cockpit as for *h* with gun ring.
	j	As in *i* with pilot in position.
	k	Decking modified and slope of wind screen modified.
	l	Decking further modified.
	m	Decking behind front cockpit trimmed at edges.
	n	Steps behind front cockpit eliminated.
	o	Wind screen No. 2 on test No. *n*.
	p	Modified decking and wind screen in permanent form; pilot in cockpit; front gun ring and quadrants in position.
5	*q*	Bomb cell cut in underside of fuselage and C.L. of tail bent up.
6	*r*	As in *q* with prone gunner's cradle in position for rear gunning.
	s	As in *r* with representative communication cut between top and bottom rear gunning positions.
7	*t*	Old type body model in final state.

The length of the model is 44.8 in.

Wind velocity on test = 60 feet per second.

The tail of the streamline has been truncated, as shown in Fig. 1, for structural reasons.

Fig. 5.—The whole centre line has been given a slight curvature.

Fig. 6.—Note the effect of air flow from top gun ring to bottom opening.

Comparison of old and new bodies: 77 lbs. against 54 lbs. Old body also does not include internal bomb stowage, and the actual effective difference is greatly increased on this account. The negative incidence of the body datum corresponding to minimum drag is due to curvature of centre line; wing incidence is, of course, greater.

TEST RESULTS.

Test *a* (Fig. 1).

The basic shape; no cockpits, etc.

Drag at 100 ft./sec. lbs.

Incidence.	Full Scale.	Drag/sq. foot.
0°	30.11	1.42
+ 2°	30.62	1.44
+ 4°	31.08	1.46
+ 6°	31.38	1.48
+ 8°	31.82	1.50
+ 10°	32.43	1.52
+ 12°	33.00	1.55
+ 14°	33.81	1.59

TEST *b* (FIG. 2).

Modified nose shape; rear cockpit cut in fuselage.

Incidence.	Drag.	Increase.
0°	30.30	0.19 lb.
+4°	31.50	0.42 ,,
+8°	32.50	0.72 ,,

TEST *c*.

Gun ring added to rear cockpit.

Incidence.	Drag.	Increase.
0°	31.20	0.9 lb.
+4°	32.02	0.52 ,,

TEST *d* (FIG. 2).

Navigator's cockpit added; gun ring removed from back cockpit.

Incidence.	Drag.	Increase.
0°	30.48	0.18 lb.
+4°	31.74	0.24 ,,

TEST *e* (FIG. 3).

Pilot's cockpit added; no gun rings; cockpits to amended sizes.

Incidence.	Drag.	Increase.
0°	32.00	1.52 lbs.
+4°	32.95	1.21 ,,

TEST *f*.

Nose gunner's cockpit and gun platform added.

Incidence.	Drag.	Increase.
−3°	36.14	—
0°	35.30	3.3 lbs.
+4°	36.84	3.89 ,,

TEST *g*.

Gun platform faired to body.

Incidence.	Drag.	
0°	35.30	} Increase
+4°	36.82	} negligible.

TEST *h*.

Scarff gun ring added.

Incidence.	Drag.	Increase.
0°	36.04	0.74 lbs.
+4°	37.44	0.62 ,,

TEST *i* (FIG. 4).

Wind screen and decking to pilot's cockpit added; front cockpit as *h*; with scarff ring.

Incidence.	Drag.	Increase.
−3°	46.22	—
0°	45.23	9.09 lbs.
+4°	48.31	10.86 ,,

TEST *j*.

As *i* plus pilot in position.

Incidence.	Drag.	Decrease.
−3°	46.22	—
0°	44.13	1.10 lbs.
+4°	46.93	1.38 ,,

TEST *k*.

Decking modified (No. 1) and slope of front wind screen panel modified.

Incidence.	Drag.	Decrease.
−3°	43.93	2.29 lbs.
0°	42.15	1.98 ,,
+4°	43.69	3.24 ,,

TEST *l*.

Decking further modified (No. 2); otherwise same as *k*.

Incidence.	Drag.	Decrease.
−3°	43.21	0.72 lbs.
0°	40.50	1.65 ,,
+4°	43.15	0.54 ,,

TEST *m*.

Decking behind front cockpit trimmed at edges.
No measurable difference from *l*.

TEST *n*.

Step behind front cockpit eliminated.

Incidence.	Drag.	Increase.
−3°	43.75	0.54 lbs.
0°	42.60	2.1 ,,
+4°	46.50	3.35 ,,

TEST *o*.

Wind screen No. 2 on *n*.

Incidence.	Drag.	
−3°	44.35	0.6 lbs. increase.
0°	42.05	0.55 ,, decrease.
+4°	45.22	1.28 ,, ,,

TEST *p*.

Modified decking and wind screen in permanent form. Pilot in cockpit; front gun ring and quadrants in position.

Incidence.	Drag.	Lbs./sq ft.	Lbs. decrease.
− 3°	41.9	1.97	2.45 lbs.
0°	39.7	1.87	2.35 ,,
+ 2°	41.1	1.94	—
+ 4°	41.9	1.97	3.32 ,,
+ 6°	43.7	2.06	—
+ 8°	44.3	2.09	—
+10°	45.4	2.14	—
+12°	46.5	2.19	—
+14°	47.4	2.24	—

TEST *q* (FIG. 5).

Bomb cell with bombs in position. Wind screens, gun rings, etc., in position.

Incidence.	Drag.	Lbs./sq. ft.	Increase.
−3°	56.0 lbs.	2.66	14.1 lbs.
0°	56.9 ,,	2.68	17.2 ,,
+2°	56.9 ,,	2.68	15.8 ,,
+4°	56.9 ,,	2.68	15.0 ,,
+6°	57.7 ,,	2.70	14.0 ,,
+8°	58.1 ,,	2.74	13.8 ,,

TEST *r* (FIG. 6).

As *q* with prone gunner's cradle in position for rear under gunning.

Incidence.	Drag.	Lbs./sq. ft.	Decrease.
−3°	54.0 lbs.	2.54	2.0 lbs.
0°	54.8 ,,	2.58	2.1 ,,
+2°	54.6 ,,	2.57	2.3 ,,
+4°	55.3 ,,	2.60	1.6 ,,
+6°	56.9 ,,	2.68	0.8 ,,
+8°	57.9 ,,	2.72	0.2 ,,

TEST *s*.

As *r*, with representative communication cut between rear top and bottom gunning pits.

Incidence.	Drag.	Lbs./sq. ft.	Increase.
−3°	56.0 lbs.	2.66	2.0 lbs.
0°	56.9 ,,	2.68	2.1 ,,
+2°	58.0 ,,	2.74	3.4 ,,
+4°	59.5 ,,	2.81	4.2 ,,
+6°	61.6 ,,	2.90	4.7 ,,
+8°	67.7 ,,	3.19	9.8 ,,

Streamers show that the flow is from the top to the bottom through the pits.

TEST *t* (FIG. 7).

Old type body model in final state.

Estimated full-scale drag at 100 ft. per second at minimum value of drag 77 lbs. Drag per sq. ft. frontal area 3.58 lbs.

APPENDIX II.

INTERFERENCE BETWEEN BODY AND MONOPLANE WING.

BODY DRAG.

Pilot's cockpit represented; no wind screen.

Thrust line Incidence.	Drag, lbs. estimated full scale at 100 f/s.	Drag lbs./sq. ft.
−4°	24.8	1.90
−2°	21.8	1.68
0°	20.7	1.59
+2°	18.6	1.43
4°	16.8	1.30
6°	18.3	1.41
8°	20.4	1.57
10°	22.3	1.71
12°	25.2	1.94

WING ALONE.

Wing incidence.	k_L	k_D, uncorrected.
$-3°$	$-.052$	.0095
$0°$	$+.064$	.0081
$+3°$	.172	.0097
$6°$	.309	.0161
$9°$	.423	.0238
$12°$	.530	.0362

BODY-WING COMBINATION.

k_D = drag, wing + interferences.

Wing incidence.	k_L	k_D, uncorrected.
$0°$	.039	.0097
$+3°$	.175	.0122
$6°$	.306	.0176
$9°$	.414	.0268
$12°$	.538	.0446

THE EFFECT ON INTERFERENCE DRAG OF VARYING THE ANGLE BETWEEN WING AND BODY.

The values shown are expressed as k_D for wing alone and residual k_D for wing body, the angle between chord of wing and centre line of body being varied from $0°$ to $+7° 16'$.

k_L	k_D Wing.	Residual k_D $0°$	Residual k_D $+4°$	Residual k_D $+5° 30'$	Residual k_D $+7° 16'$
0	.0084	.0077	.0077	.0094	.0102
.1	.0078	.0078	.0088	.0094	.0097
.2	.0105	.0102	.0106	.0122	.0130
.3	.0150	.0150	.0146	.0168	.0177
.4	.0216	.0228	.0229	.0248	.0248
.5	.0322	.0337	.0350	.0385	.0377

BODY-WING INTERFERENCE IN LBS. FULL SCALE AT 100 F/S.

	Angle between wing and body			
k_L	$0°$	$4°$	$5° 30'$	$7° 16'$
0	− 6.5	− 6.5	+ 9.3	+16.8
.1	0	+ 1.9	+14.9	+17.8
.2	− 2.8	+ 0.9	+15.9	+23.4
.3	0	− 3.7	+16.8	+25.2
.4	+11.2	+12.1	+29.9	+29.9
.5	+14.0	+26.3	+56.8	+51.4

REMARKS.

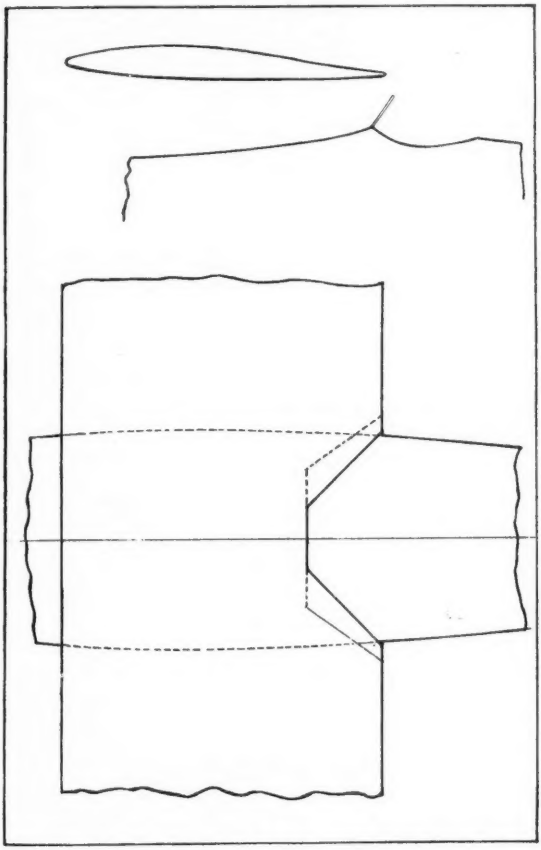
(1) It has not been possible to eliminate body-wing interference over the whole range of k_L.

(2) The interference can be kept reasonably small at values of k_L above .4 and negligibly small at values of k_L below .4, if the angle between the chord line of the wing and the centre line of the body be not allowed to exceed $+4°$.

Model tested at $Vl = 38.5$. l = chord of wing.

" Uncorrected " means uncorrected for channel walls, as difference effect is being studied.

APPENDIX III.



BODY WINGS INTERFERENCE OVER A RANGE OF INCIDENCE.

Model, 1/4 scale; span restricted to 3 ft. 6 in.; Jupiter engine; pilot and wind screen; no tail unit.

Results shown are observed 1/4 scale at 60 f.p.s.

Wing Inc.	Drag lbs. Model Complete. (1)	Biplane (2)	Body, etc. (3)	Lift lbs. Sum. (2)+(3)	Interference. (1)−(2+3)	Interfer. Lift.
−2°	3.005	1.289	1.2938	2.5829	+.424	+2.869
0°	2.755	1.308	1.2907	2.5987	+.158	+1.408
+2°	3.244	1.509	1.2922	2.8012	+.443	+0.868
+4°	3.629	1.854	1.3113	3.1653	+.464	−1.514
+6°	3.970	2.223	1.3130	3.5360	+.434	+2.525

REMARKS.

(1) There is an interference effect present which does not increase with incidence.
(2) The interference drag at +2° amounts to +19.7 lbs. full scale 100 f./s.
(3) It is probably due to the congestion at the centre section and must be found and corrected.

INTERFERENCE ANALYSED.

CHANNEL REFERENCE.—+2° incidence was chosen for a complete analysis; drags lbs. estimated full scale at 100 f.p.s.

Item.	Interference Drag.
Total interference drag to be accounted for	+19.7 lbs.
Interference of pilot, wind screen and head fairing on biplane model	+ 3.59 ,,
Effect of flattening wind screen to 45°	—
Interference between body and bottom wing	+ 2.59 ,,
Interference between top wing and body	+ 4.60 ,,
Effect of side plates	—
Interference of body on top wing	+ 5.57 ,,
Effect of side plates	+ 0.81 ,,
Calculated biplane effect (Prandtl)	+ 1.42 ,,
Synthetic total	18.58 ,,
By observations on complete model	19.70 ,,
Discrepancy	− 1.12 ,,

THE EFFECT OF ENLARGING THE CUTAWAY.

The results are shown as lbs. estimated full scale at 100 ft./sec.; interferences to be dealt with and extent to which the modifications were successful.

	Interference Drag.		Interference Lift.	
Wing Incidence.	Old Scheme.	New Scheme.	Old Scheme.	New Scheme.
−2°	+18.86	+4.41	+127.5	+105.5
0°	+ 7.20	−2.10	+ 62.5	+ 92.8
+2°	+19.70	+2.0	+ 38.6	+ 72.5
+4°	+20.64	−2.84	− 67.2	− 3.1
+6°	+19.25	+3.73	+112.3	+162.5

REMARKS.

(1) Interference lift includes body lift, not separately measured, but always +.
(2) With the new cutaway, wind screen, pilot and head fairing are mounted for the same drag, viz., 2.00 lbs., as on body only.
(3) Restoring the model from new cutaway to old by plasticine, as a check, gave drag value 3.242 lbs. against the original figure of 3.262 lbs. for the old original cutaway—a reasonable repeat.

NOTE.—The side plates referred to are those used for the structure of the model to connect the wing tips.

APPENDIX IV.

1/5.9 SCALE MODEL TEST RESULTS.

MUTUAL INTERFERENCE OF WINGS AND BODY.

A. BOTTOM PLANE AND BODY.

Observed drags at 60 ft./sec. and estimated full-scale interference drags.

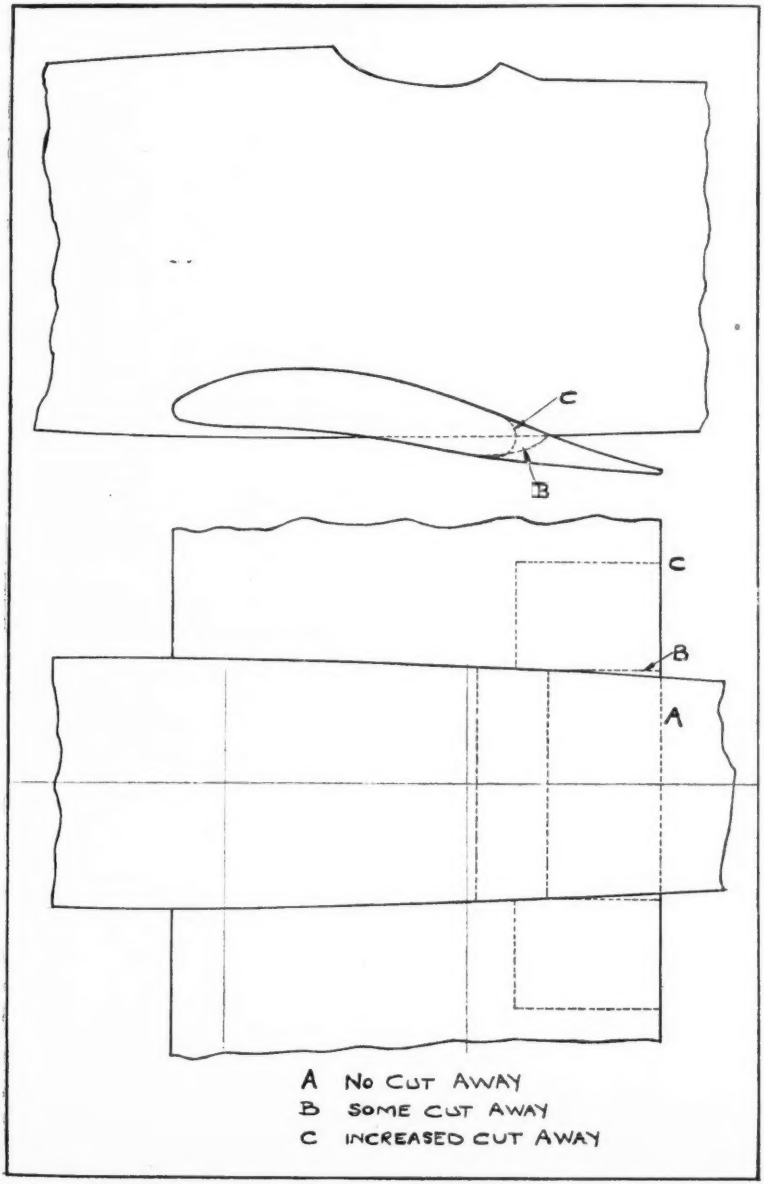
Wing Incidence.	Body.	Bottom Wing.	Sum.	Combination.	Interference. Observed.	Interference. Full Scale 100 f/s.
0°	0.6218	0.4592	1.0810	1.1290	0.0480	+ 4.63 lbs.
+4°	0.5860	0.5472	1.1332	1.3230	0.1898	+18.3 ,,
+8°	0.6260	1.2850	1.9110	2.1520	0.2410	+23.2 ,,

B.

0°	0.6218	0.4592	1.0810	1.1080	0.0270	+ 2.61 lbs.
+4°	0.5860	0.5472	1.1332	1.2595	0.1263	+12.20 ,,
+8°	0.6260	1.2850	1.9110	2.0959	0.1849	+17.9 ,,

C.

0°	0.6218	0.4592	1.0810	1.0210	−0.0600	−5.8 lbs.
+ 4°	0.5860	0.5472	1.1332	1.1350	+0.0018	+0.17 ,,
+ 8°	0.6260	1.2850	1.8110	1.9134	+0.0024	+0.23 ,,
+12°	0.6610	2.3087	2.9698	2.9810	+0.0014	+0.13 ,,



Appendix V.

R.A.F. 15 BIPLANE WITH TWO JUPITER NACELLES MOUNTED BETWEEN PLANES.

Total area of wings—925 square feet.

Incidence degrees.	k_L	% Loss of Lift (2 nacelles).	lbs. at 100 ft./sec. Full Scale. Interference Lift	lbs. at 100 ft./sec. Full Scale. Interference Drag
−3	−.019	0	—	+ 23.6
0	+.102	9.9	− 220	+ 10.4
+3	+.196	2.6	− 112	+107.6
+6	+.310	8.7	− 588	+ 68.6
+9	+.410	13.5	−1212	+131.6

R.A.F. 15 BIPLANE WITH TWO LION NACELLES MOUNTED ON BOTTOM WING.

−3	−.019	0	+ 166	+ 8
0	+.102	3.9	− 86	−18
+3	+.196	4.0	− 174	− 8.6
+6	+.310	10.5	− 714	+30
+9	+.410	10.9	− 980	+70

TWO LION NACELLES; BOTTOM PLANE EFFECT ONLY.

−3	−.019	0	—	− 14
0	+.102	4.5	− 100	− 8
+3	+.196	12.6	− 540	− 2
+6	+.310	10.8	− 732	+104
+9	+.410	12.7	−1140	+184

The magnitude of the interference on lift can be estimated from the fact that at 9° the total lift would be 8,990 lbs. at 100 feet per second.

APPENDIX VI.

LOW WING MONOPLANE. WING-STRUT INTERFERENCE.

Model scale: 1/5.25. Strut $vl=3.6$. Wing $vl=80$. Strut 18 in. long, one end free. Channel speed=60 f.p.s.
Drag of 18 in. strut and one free end at 60 f.p.s. with no wing interference=0.0386 lbs.

TEST RESULTS.

The figures given below represent—

(1) The extra cost (in lbs.) of mounting the strut, with one free end, on the wing, measured over a range o
(*a*) wing incidence, (*b*) strut inclinations.

(2) The percentage of total mutual interference on the figure 0.0386 lbs. given above.

(3) The effect on wing lift.

No Lift: −2.1° Inc.			k_L.061: −0.4° Inc.			k_L.157: +2.2° Inc.			k_L.242: +4.6° Inc.			Angle of Strut.
Interference lbs.	Drag. %	Interference Lift lbs.	Interference lbs.	Drag. %	Interference Lift lbs.	Interference lbs.	Drag. %	Interference Lift lbs.	Interference lbs.	Drag. %	Interference Lift lbs.	
+.0138	+35.7	+.015	+.0156	+40.4	−.022	+.0155	+40.2	−.016	+.0156	+40.4	−.012	90°
+.0148	+38.4	+.018	+.0179	+46.4	−.028	+.0158	+40.9	−.007	+.0194	+50.2	−.059	45°
+.0163	+42.3	+.034	+.0248	+64.2	−.070	+.0277	+71.7	−.029	+.0276	+71.6	−.116	30°
+.0203	+52.6	+.028	+.0348	+90.1	−.112	+.0379	+98.2	−.042	+.0377	+97.8	−.192	20°
+.0248	+64.2	+.026	+.0430	+111	−.134	+.0411	+106	−.051	+.0426	+110	−.231	15°
+.0727	+188	+.025	—	—	−.252	+.0676	+175	−.129	+.0695	+180	−.542	10°

Further range of incidence +7° and +10°. Model results at 60 f.p.s.

	+7° Inc. k_L=.318		+10° Inc. k_L=.431	
Strut Angle.	Interference Drag.	Interference Lift.	Interference Drag.	Interference Lift.
90°	+.0151 lbs.	−.005 lbs.	+.0193 lbs.	−.0114 lbs.
45°	+.0161 ,,	−.0300 ,,	+.0207 ,,	−.0562 ,,
30°	+.0292 ,,	−.0860 ,,	+.0344 ,,	−.1240 ,,
20°	+.0433 ,,	−.1730 ,,	+.0484 ,,	−.2050 ,,
15°	+.0505 ,,	−.2472 ,,	+.0558 ,,	−.2836 ,,
10°	+.0817 ,,	−.4100 ,,	+.0858 ,,	−.4330 ,,

Below the interferences for one strut are shown as Δk_D and Δk_L for the monoplane at various values of k_L.

Strut	k_L=0		k_L=.061		k_L=.157		k_L=.242		k_L=.318		k_L=.431	
Angle.	Δk_D	Δk_L	Δk_D	Δk_L	Δk_D	Δk_L	Δk_D	Δk_L	Δk_D	Δk_L	Δk_D	Δk_L
90°	+.00016	+.00017	+.00018	+.00027	+.00018	−.00018	+.00018	−.00014	+.00017	−.00006	+.00022	−.00013
45°	+.00017	+.00021	+.00021	−.00032	+.00018	−.00008	+.00022	−.00068	+.00019	−.00035	+.00024	−.00065
30°	+.00019	+.00039	+.00029	−.00081	+.00032	−.00033	+.00032	−.00134	+.00034	−.00099	+.00040	−.00143
20°	+.00023	+.00032	+.00040	−.00129	+.00044	−.00048	+.00043	−.00222	+.00050	−.00200	+.00056	−.00237
15°	+.00029	+.00030	+.00050	−.00155	+.00047	−.00059	+.00049	−.00267	+.00058	−.00285	+.00065	−.00328
10°	+.00084	+.00029	—	−.00291	+.00078	−.00149	+.00080	−.00626	+.00094	−.00473	+.00099	−.00509

Remarks and Summary.

(1) At 90° the best angle for a strut to meet an aerofoil, the cost of the end in drag corrected for scale effect, is

0.85 lb. full-scale at 100 ft./sec. at $k_L=0$.
1.18 ,, ,, ,, at $k_L=.431$.

(2) The drag values shown in the table are subject to a correction of −20 per cent. for scale effect.

(3) The strut used in the investigations has an observed drag (without end effects) of 1.06 lbs. per square foot projected area at 100 ft./sec. This becomes 0.85 lb./sq. ft. when corrected for scale effect.

(4) The strut enters the wing cleanly at all angles—all end fittings are embedded in the wing and the wing made good.

(5) The figure usually taken for end effect with sockets for struts is 0.2 lbs. per end at 100 ft./sec. The figure now obtained of 0.85 to 1.18 lbs. per end includes the total interference drag between aerofoil and strut at 90° strut angle. The existence of this interference does not appear to have been previously determined experimentally, or expected. Further investigation will be necessary to ascertain to what extent such interference would vary with location of the strut along the chord.

(6) As an indication of the effect at full scale, for a monoplane of 40 feet span and 7 feet chord, with four such struts at an angle of 30°, the figures, expressed in lbs. at 100 feet per second, would be:—

Interference drag = +4.00 lbs. at $k_L=0$.
+ 8.4 lbs. at $k_L=.431$.

Interference lift = +10.4 lbs. at $k_L=0$.
−38.0 lbs. at $k_L=.431$.

(7) In the worst case dealt with, viz., with the strut at 10°, the interferences become much more serious at the values shown:—

Δk_D = +.00269 at $k_L=0$.
= +.00317 at $k_L=0.431$.

Or expressed in lbs. at 100 feet per second:—

Interference drag = 19.8 lbs. at $k_L=0$.
= 21.1 lbs. at $k_L=0.431$.

Δk_L = +.00116 at $k_L=0$.
= −.02000 at $k_L=0.431$.

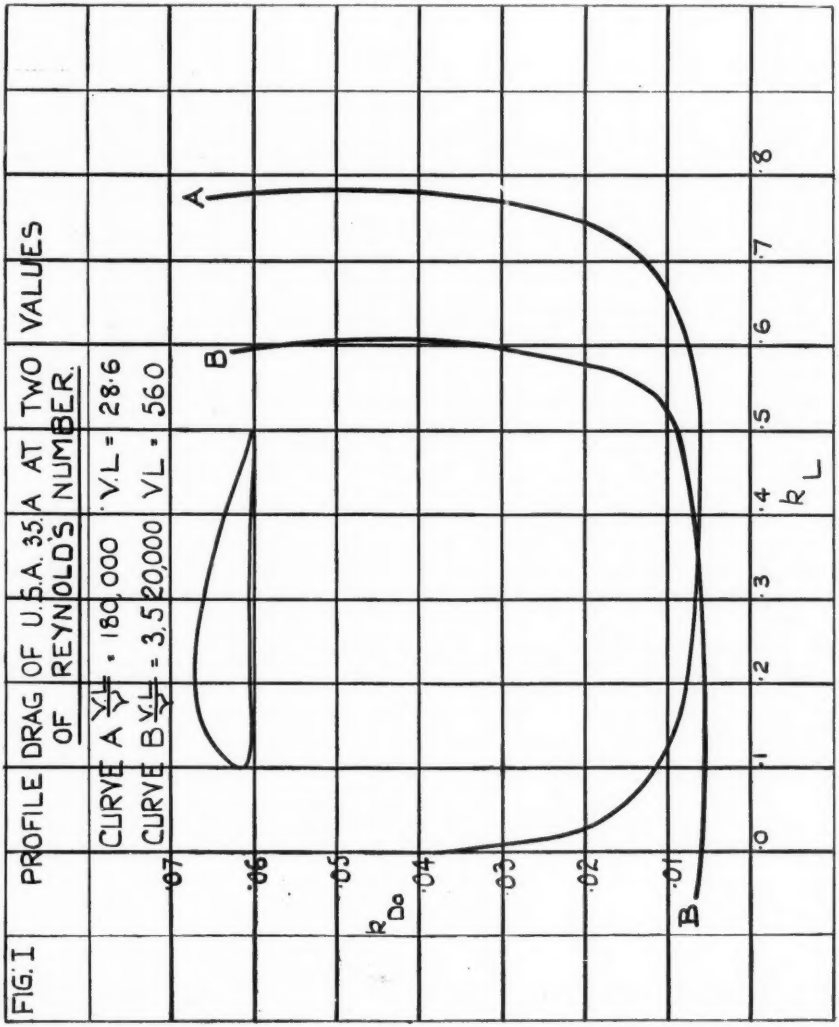
Lbs. at 100 feet per second:—

Interference lift = +7.6 lbs. at $k_L=0$.
= −130 lbs. at $k_L=0.431$.

Appendix VII.

Full details of the tests on which these curves are based are given in N.A.C.A. 1926 Report No. 233.

Figs. 2 and 3 are adapted from "Aerodynamics," by E. P. Warner.



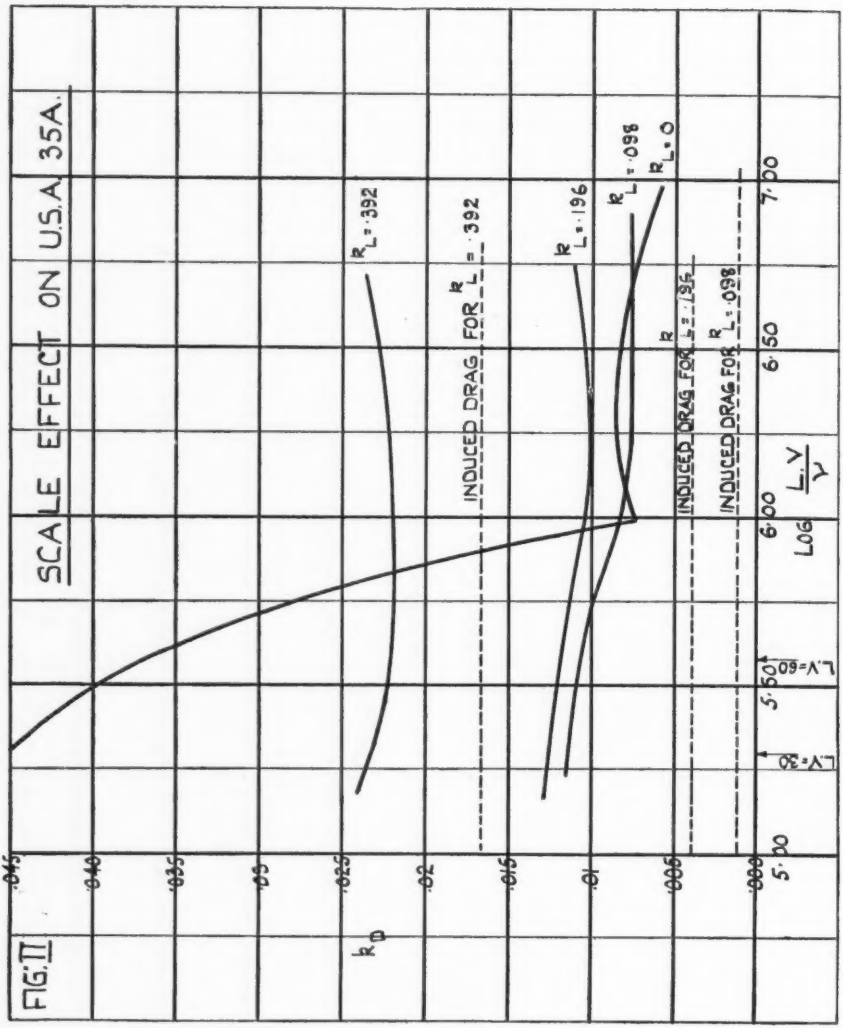
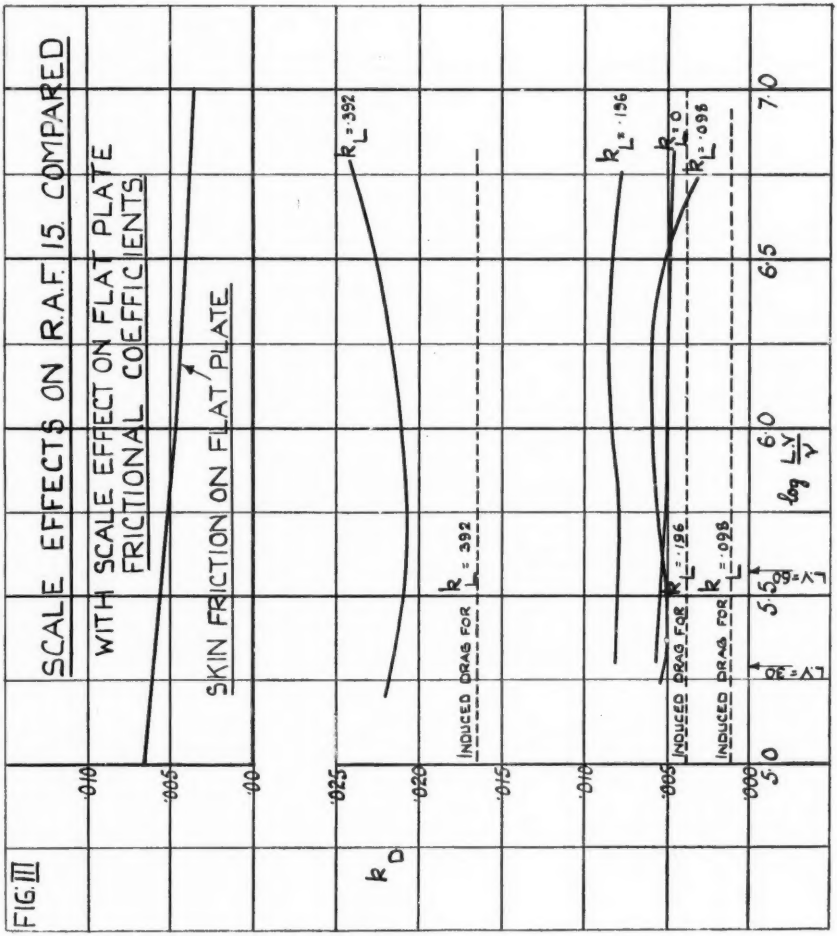


FIG. II
SCALE EFFECT ON U.S.A. 35A.
C_D
.045
.040
.035
.03
.025
.02
.015
.01
.005
.000
$R_L = .392$
INDUCED DRAG FOR $R_L = .392$
$R_L = .196$
$R_L = .098$
$R_L = 0$
INDUCED DRAG FOR $R_L = .196$
INDUCED DRAG FOR $R_L = .098$
5.00
5.50
6.00
6.50
7.00
LOG $\frac{L.V}{\nu}$
$L.V = 60$
$L.V = 30$



APPENDIX VIII.

Analysis of frictional and turbulence drags on three aeroplanes, including direct interference.

A. Single-engined military biplane.
B. Twin- ,, ,, ,,
C. Triple- ,, ,, ,,

CHARACTERISTICS.

	W/S.	W/H.P.	Span²/W.
A.	9.52	7.04	.345
B.	8.88	9.8	.586
C.	9.45	15	.492

Surface is not reduced for presence of body, except for calculation of profile drag.

Table I. is on a percentage basis.

Tables II. and III. are percentages on total drag in Table I.

Air-cooled radial engines: A and B, direct drive; C, geared.

PERCENTAGES OF TOTAL—NO SLIPSTREAM.

	A.			B.			C.		
WINGS.	In S.S.	Out S.S.	Total.	In S.S.	Out S.S.	Total.	In S.S.	Out S.S.	Total.
Profile	2.00	25.85	27.85	1.69	21.00	22.69	3.97	24.48	28.45
Struts and wires	0.70	5.46	6.16	2.95	8.20	11.15	2.45	10.00	12.45
Interferences due to struts and wires	1.49	3.12	4.16	1.91	4.29	6.20	1.25	3.22	4.47
	4.19	34.43	38.17	6.55	33.49	40.04	7.67	37.70	45.37
BODY.									
Body, all on	14.95	0.00	14.95	0.00	11.82	11.82	0.00	10.15	10.15
Body = wing interference ...	1.36	0.00	1.36	0.00	0.00	0.00	0.00	0.78	0.78
	16.31	0.00	16.31	0.00	11.82	11.82	0.00	10.93	10.93
ENGINES.									
Nacelles	0.00	0.00	0.00	7.23	0.00	7.23	5.94	0.00	5.94
Cooling	20.35	0.00	20.35	17.67	0.00	17.67	14.18	0.00	14.18
Interferences	0.00	0.00	0.00	4.90	0.00	4.90	2.35	0.00	2.35
	20.35	0.00	20.35	29.80	0.00	29.80	22.47	0.00	22.47

LANDING GEAR.									
Wheels	0.00	6.56	6.56	1.69	1.69	3.38	0.46	3.25	3.71
Oleo	0.55	0.84	1.39	2.27	0.00	2.27	1.24	1.24	2.48
Struts, wires and axles ...	1.34	2.42	3.76	0.82	0.75	1.57	1.18	1.13	2.31
Skid	1.36	0.00	1.36	0.00	1.02	1.02	0.00	1.12	2.12
Interferences	1.09	1.30	2.39	0.77	0.78	1.55	0.71	1.32	2.03
	4.34	11.12	15.46	5.55	4.24	9.79	3.59	8.06	11.65
EMPENNAGE.									
T.P. profile	1.10	0.93	2.03	0.92	1.63	1.63	0.00	2.40	2.40
Fin and rudder	1.07	0.00	1.01	0.00	1.22	1.22	0.00	1.21	1.21
Struts	0.76	0.00	0.76	0.00	0.65	0.65	0.18	1.22	1.40
Interferences	2.21	0.00	2.21	0.00	1.26	1.20	0.22	1.21	1.43
	5.14	0.93	6.07	0.92	4.76	5.68	0.40	6.04	6.44
MISCELLANEOUS.									
External controls, etc. ...	2.06	1.13	3.19	0.93	1.94	2.87	0.85	2.29	3.14
	2.06	1.13	3.19	0.93	1.94	2.87	0.85	2.29	3.14
TOTALS	52.39%	47.61%	100.00%	43.75%	56.25%	100.00%	34.98%	65.02%	100.00%

TOP SPEED.

Percentages in slipstream multiplied by estimated average values of R/R_0 for top speed, *i.e.*, $R/R_0 = 1.5$ for ungeared and 1.4 for geared engines.

	A.			B.			C.		
WINGS.	In S.S.	Out S.S.	Total.	In S.S.	Out S.S.	Total.	In S.S.	Out S.S.	Total.
Profile	3.00	25.85	28.85	2.53	21.00	23.53	5.56	24.48	30.14
Struts and wires	1.05	5.46	6.51	4.42	8.20	12.62	3.43	10.00	13.43
Interferences due to struts and wires	2.23	3.12	5.35	2.86	4.29	7.15	1.75	3.22	4.97
	6.28	34.43	40.71	9.81	33.49	43.30	10.74	37.70	48.44
BODY.									
Body, all on	22.42	0.00	22.42	0.00	11.82	11.82	0.00	10.15	10.15
Body = wing interference ...	2.04	0.00	2.04	0.00	0.00	0.00	0.00	0.78	0.78
	24.46	0.00	24.46	0.00	11.82	11.82	0.00	10.93	10.93
ENGINES.									
Nacelles	0.00	0.00	0.00	10.85	0.00	1.00	8.32	0.00	8.32
Cooling	30.52	0.00	30.52	26.50	0.00	26.50	19.85	0.00	19.85
Interferences	0.00	0.00	0.00	7.35	0.00	7.35	3.29	0.00	7.35
	30.52	0.00	30.52	44.70	0.00	44.70	31 46	0.00	31.46

LANDING GEAR.									
Wheels	0.00	6.56	6.56	2.53	1.69	4.22	0.64	3.25	3.89
Oleo	0.82	0.84	1.66	3.40	0.00	3.40	1.73	1.24	2.97
Struts, wires and axles ...	2.01	2.42	2.43	1.23	0.75	1.98	1.65	1.13	2.78
Skid	2.04	0.00	2.04	0.00	1.02	1.02	0.00	1.12	1.12
Interferences	1.63	1.30	2.93	1.15	0.78	1.93	0.99	1.32	2.31
	6.50	11.12	17.62	8.31	4.24	12.55	5.01	8.06	13.07
EMPENNAGE.									
T.P. profile	1.65	0.93	2.58	1.38	1.63	3.01	0.00	2.40	2.40
Fin and rudder	1.60	0.00	1.60	0.00	1.22	1.22	0.00	1.21	1.21
Struts	1.14	0.00	1.14	0.00	0.65	0.65	0.25	1.22	1.47
Interferences	3.31	0.00	3.31	0.00	1.26	1.26	0.31	1.21	1.52
	7.70	0.93	8.63	1.38	4.76	6.14	0.56	6.04	6.60
MISCELLANEOUS.									
External controls, etc. ...	3.09	1.13	4.22	1.39	1.94	3.33	1.19	2.29	3.48
	3.09	1.13	4.22	1.39	1.94	3.33	1.19	2.29	3.48
TOTALS	78.55%	47.61%	126.16%	65.59%	56.25%	121.84%	48.96%	65.02%	113.98%

CLIMB.

Percentages in slipstream multiplied by $R/R_o = 3.0$ for ungeared engines and 2.5 for geared engines.

	A.			B.			C.		
WINGS.	In S.S.	Out S.S.	Total.	In S.S.	Out S.S.	Total.	In S.S.	Out S.S.	Total.
Profile	6.00	25.85	31.85	5.07	21.00	26.07	9.92	24.48	34.40
Struts and wires	2.10	5.46	7.56	8.85	8.20	17.05	6.13	10.00	16.13
Interferences due to struts and wires	4.47	3.12	7.59	5.73	4.29	10.22	3.12	3.22	6.34
	12.57	34.43	47.00	19.65	33.49	53.14	19.17	37.70	56.87
BODY.									
Body, all on	44.84	0.00	44.84	0.00	11.82	11.82	0.00	10.15	10.15
Body = wing interference ...	4.08	0.00	4.08	0.00	0.00	0.00	0.00	0.78	0.78
	48.92	0.00	48.92	0.00	11.82	11.82	0.00	10.93	10.93
ENGINES.									
Nacelles	0.00	0.00	0.00	21.69	0.00	21.69	14.85	0.00	14.85
Cooling	61.04	0.00	61.04	53.00	0.00	53.00	35.45	0.00	35.45
Interferences	0.00	0.00	0.00	14.70	0.00	14.70	5.87	0.00	5.87
	61.04	0.00	61.04	89.39	0.00	89.39	56.17	0.00	56.17

LANDING GEAR.									
Wheels	0.00	6.56	6.56	5.07	1.69	6.76	1.15	3.25	4.40
Shock absorbing mechanism	1.65	0.84	2.49	6.81	0.00	6.81	3.10	1.24	4.34
Struts, wires and axles ...	4.02	2.42	6.44	2.46	0.75	3.21	2.95	1.13	4.08
Skid	4.08	0.00	4.08	0.00	1.02	1.02	0.00	1.12	1.12
Interferences	3.27	1.30	4.57	2.31	0.78	3.09	1.78	1.32	3.10
	13.02	11.12	24.14	16.65	4.24	20.89	8.98	8.06	17.04
EMPENNAGE.									
T.P. profile	3.30	0.93	4.23	2.76	1.63	4.39	0.00	2.40	2.40
Fin and rudder	3.21	0.00	3.21	0.00	1.22	1.22	0.00	1.21	1.21
Struts	2.28	0.00	2.28	0.00	0.65	0.65	0.45	1.22	1.67
Interferences	6.63	0.00	6.63	0.00	1.26	1.26	0.55	1.21	1.76
	15.42	0.93	16.35	2.76	4.76	7.52	1.00	6.04	7.04
MISCELLANEOUS.									
External controls, etc. ...	6.18	1.13	7.31	2.79	1.94	4.73	2.13	2.29	4.42
	6.18	1.13	7.31	2.79	1.94	4.73	2.13	2.29	4.42
TOTALS	157.15%	47.61%	204.76%	131.24%	56.25%	197.49%	87.45%	65.02%	152.47%

Discussion

Mr. H. E. Wimperis (Director of Aeronautical Research): The subject Mr. North has chosen for his lecture is one of urgent importance at the moment. He asked if Mr. North would explain the exact meaning of his word "affine." The subject of interference between aeroplane parts was one which had been brought to his attention very forcibly indeed during the last year or two, in view of the efforts which had been made to build very high speed aircraft which afterwards would be used to compete for the Schneider Trophy. In the course of the work carried out in the wind tunnels at the National Physical Laboratory—the results of which would be published in due course—very singular interferences were found and, largely as a matter of trial and error, means of reducing them were discovered. The "Crusader" had not survived long enough to enable its possible speed to be ascertained, but in the wind tunnel tests on the model of that machine and the other machines by repeated attention to detail and by appropriate cowling of the cylinders, the resistance was reduced to a very remarkable degree. The resistance was decreased to such an extent that there was very little difference between the "Crusader" model and the other two. Mr. North had drawn attention to the difficulty of studying interference effects in ordinary wind tunnels, because of the impossibility, in the first instance, of making models really true to scale except at prohibitive cost, *i.e.*, true to scale as regards the smallest detail and, even if one were able to do that, the Reynolds' number would be such that one would not be able to obtain the right result; it would be far too low, particularly for the smaller fittings. The Reynolds' number could be increased, however, by building a compressed air tunnel such as that possessed by the Americans, and such a tunnel was being constructed at the National Physical Laboratory, at a cost of something over £50,000. That tunnel would be of very great value indeed for the elucidation of some of the problems Mr. North had mentioned, but, of course, it would not enable some of the points we wanted to clear up to be solved in regard to the smaller fittings.

With that tunnel it would be possible to study interference effects on clean designs, but when it came to designs which had to embody operational requirements—not the "technical" requirements of the Air Ministry, as journalists often supposed—it would not be necessary to carry out experiments on the full scale. If that were to be done a new kind of tunnel altogether would be required, having regard to the difficulties and expense of carrying out such tests in free flight. In America there was a tunnel 20 ft. in diameter, into which could be introduced complete but small machines, and the experiments carried out in that tunnel were most revealing. In the view of the speaker, a tunnel of that kind was needed here, and he was glad to be able to say that the Ministry had it under consideration, and was being advised thereon by the Aeronautical Research Committee. It would cost as much as a large flying boat, but it would enable a wind speed in it of 100 miles an hour to be attained and it would be worth the cost. In such a tunnel interference effects could be studied, and a much more detailed study made than was previously possible on propeller efficiency also—a matter very much outstanding at the present time. Furthermore, it would be possible to make some study of the influence of pusher and tractor engines on interference effects. At present the pusher engines were so placed that they disturbed the air very much indeed before it came on to any aerodynamic surfaces at all. In experiments on "flutter" carried out at the National Physical Laboratory it had been shown in certain cases that when the air stream was turned on, the model was entirely steady, but if one pushed a rod into the air stream ahead of the model and then withdrew it, there was a collapse. That was an indication of the way in which a disturbance of the air might build up. If the Air Ministry decided that the air tunnel he had referred to should be built, it ought to go far to solve a good many of the points raised

by Mr. North, but he would be glad if Mr. North would indicate whether, in his view, experiments in such a tunnel would determine all the problems he had in mind, and what precautions ought to be taken to ensure that it was used to the fullest advantage for that purpose.

Captain W. H. SAYERS: He was particularly interested in Mr. North's remarks on induced interference, but could not admit the claim that it was mentioned for the first time in Mr. North's paper. In the Aeronautical Engineering Supplement to *The Aeroplane* of June 13th, 1923, there was published a note concerning interference, in which it was reported that the Eiffel Laboratory had found that the interference on certain model wings caused by differing arrangements of the supports was confined entirely to the induced drag, and could be represented as equivalent to a change in aspect ratio. In some comments on that test he had suggested that the reason why interference drags of the order shown by the report had not been noticed in full-scale machines was that the interference effects were in opposite directions on top and bottom wing and tended to cancel out, a fact which was confirmed by Mr. North's statement that "This effect of the apparent reduction of bottom plane interference by the presence of the top wing is quite common." Mr. North had made it clear that he confined the term "induced interference" to cases affecting aerofoil sections or similar bodies in which the change of drag could be represented as equivalent to change in aspect ratio. He (Captain Sayers) had long held that all interference effects, if they could not be included under the term "induced interference," were of a somewhat similar nature. If any symmetrical body were introduced unto a uniform air stream the disturbance around that body was symmetrical and there was no cross wind force on the body. If a second body were introduced into the same air stream the disturbance ceased to be symmetrical with respect to either body, and there were cross wind forces on both of them. If the cross wind force were produced on an aerofoil its effect could be computed in the shape of induced drag, if one knew what the actual distribution was. Where the body was of a type not capable of acting as an efficient aerofoil the flow which accompanied the cross wind force might be exceedingly turbulent. The drag would then be much higher than the corresponding induced drag, but he believed that in looking for types of flow likely to set up cross wind forces on the body one could get a qualitative idea of whether interference was likely to occur and whether it was likely to be serious or not.

Mr. MCKINNON WOOD: Mr. North had given a definition of "technique"; he would suggest another definition, namely, "the art of design is the art of seeing things as a whole." The considerations Mr. North had put forward supported that idea. A good many people, both in aeronautical design and research, suffered rather from a pseudo-scientific analytical habit of mind; they hoped that in some mysterious way the resistance of combinations of bodies might be dealt with by some sort of aerodynamic Ohm's law. He would not suggest that the intelligence of the human mind was not such that one could come to some conclusions, by pure reason, about interference effects; the thing was not an entire mystery, although one was frequently completely deceived in one's predictions, but the idea of doing aerodynamics by the yard was certainly wrong. The second paragraph of Mr. North's paper particularly appealed to him; he agreed that "it is perhaps unfortunate that flying machines can be produced in extreme forms." If he were his own master, he would pursue systematic research on those lines only which he considered promising. The difficulty, of course, was that he would be guided solely by his own opinion as to what was promising. If the best people were retained for research, they would certainly produce good things in this way; but it was equally certain that they would pass by many good things because they were so wrapped up in those things upon which they were actually engaged. It was certainly difficult to draw the

line between pursuing rigidly a systematic line of research, and continually turning aside to have a really thorough look at novelties as one went along. In reading the paper, he had felt that it led to the conclusion Mr. North had indicated when he had referred to the large tunnel. Mr. North, who was not simply an aerodynamicist, had devoted his paper to dealing with " those aspects of aeroplane design in which there lie potential troubles and difficulties for the aeronautical engineer," and had stated that " these stood in the way of advance." The paper consisted, in the main, of aerodynamic questions, and they were all problems which could be very much more quickly solved, or in the solution of which progress could be made most quickly, by the use of a large wind tunnel. As Mr. North had said, there were two difficulties in regard to wind tunnel results; one was the difficulty that the models were insufficiently representative of the full-scale aeroplanes and the other was the problem of scale effect. Mr. North had attached most importance to the former, and he was not sure that Mr. North was not right. If and when a large wind tunnel was in use, in which the actual fuselage of an aeroplane could be placed, it would be extraordinarily interesting to treat the fuselage with fabric and glue, putty and such things, covering over the minor excrescences, such as the lacing of the fabric. He had tested in a wind tunnel an aeroplane wheel with fabric over the spokes, and another wheel on which the fabric had been stretched carefully from the side of the tyre to fill up the hollows. A test was carried out on a wooden representation of the wheel, and the drag fell to two-thirds. On the actual wheel there was no difference whatever until a gap between the fabric and the tyre was covered over; the air had been getting into that little gap, flowing round the tyre and inside the fabric instead of outside it. With regard to Mr. North's statement that a ten per cent. reduction in the total drag of an aeroplane at top speed at ground level would, on an aeroplane with a big speed range, make a difference of only about $2\frac{1}{2}$ per cent. on top speed, he said that surely the advance in speed resulting from a 10 per cent. decrease in drag would be more like $3\frac{1}{3}$ per cent. With regard to cooling, he had made some calculations of the amount of power that must necessarily be spent in cooling an engine, without using water cooling, but by direct air cooling, and had concluded that from 1 to 2 per cent. of the brake horse-power was all that need be so spent. The actual figures of present practice, he supposed, averaged ten times that amount, and frequently more than that in very fast aeroplanes. From that primitive calculation to the production of an engine in which the cooling was effected as economically as was indicated was a very long step; perhaps from 10 to 20 years would elapse before such an engine was produced.

Major BUMPUS: He thanked Mr. North for the information given as to the methods which he used in analysing the drag of a model. It was very instructive, for instance, to compare the two bodies, the one drawn to fulfil the various operational requirements and then faired in, and the other starting from a perfect basic shape and modified step by step to meet the operational requirements, and it was notable that the latter, while giving equal facilities to the crew, had only about two-thirds of the drag of the former. It was not many years since those connected with aeroplane design had thought that they could, within certain limits, add together the resistances of the various components of an aeroplane and, with some modest allowance for interference, predict reasonably the forms they were out to get. This was one of the cases in which the further one proceeded the more one realised how little one knew, and experiments such as Mr. North had described tended to show that these interference effects could not be predicted, but that they were of very great moment. Commenting on the paper by Professor Jones, mentioned by Mr. North in the paper, he said that as one concerned with the actual production of machines he would be interested to know if anyone could give an indication of how to get away

from the turbulence Professor Jones had referred to. It was very enticing to a designer to be told that the power absorbed in climb, for instance, need be only two-thirds of what was at present absorbed, and that the power at top speed need be only about one-third, but he had failed to find any sort of clue as to how to get rid of the class of turbulence referred to, and if Mr. North could give a hint, designers generally would be extremely grateful to him. Research with a view to finding alternative schemes of cooling air-cooled engines so that there should be less drag due to interference needed to be pursued very thoroughly. There were so many advantages in the use of the air-cooled engine, both as regards weight and simplicity, that there was every inducement to effect a reduction in resistance.

Major Wimperis had stated that in the tests on the various Schneider Trophy machines the drag of the "Crusader," with an air-cooled engine, was reduced to very nearly the same figure as the drag of the machines with water-cooled engines. In view of the fact that the water-cooled engines had radiators which gave no drag, that statement must imply that the drag of the air-cooled engine was reduced to something like the drag of the water-cooled engine without radiator. If that had been done it would seem that there would be opened up a very wide field for the air-cooled engine, for designers had had at the back of their minds the notion that, while the air-cooled engine might have advantages as regards weight, maintenance, and so on, it was and must always be essentially a worse engine than the water-cooled engine from the point of view of drag.

Mr. F. Handley Page: He was glad Mr. North had dealt with the problem of interference between bodies and wings, because he considered that in that direction lay the greatest scope for improvement in design. In the paper Mr. North had shown how the aerodynamic features and the operational features of an aeroplane were completely antagonistic. For instance, reference had been made to induced drag on the tail and to interference between struts and planes; the question was raised as to whether it was worth while, from the aerodynamic point of view, dispensing with external bracing, and attention was drawn to the fact that the high-speed machines were externally braced. Against that there was the operational requirement that a man firing aft wanted to fire round a tail which had no bracing wires, so that he could have a larger arc of fire. Consequently, one could not take full advantage of what might be the best arrangement aerodynamically, as was the case so often in aeroplane construction. With regard to the appendices to the paper, he said that in Appendix I. there were some very valuable diagrams of the shapes of bodies from which eventually Mr. North had evolved a new type of body, giving a much lesser drag than former bodies. If, in Appendices II., IV. and VIII., sketches could be given showing the actual positions of the planes relative to the body and the shape of the bodies to which the planes were attached, for both the low wing and high wing positions, the value of the figures given in those appendices would be greatly enhanced. If the same information could be given also in regard to the Jupiter nacelles mounted between the planes (Appendix V.), one would be able to get a better picture of what the figures actually referred to. Again, in regard to Appendix VIII., in which the drag of the different portions of three machines was compared, it would be valuable to have figures showing the total drag of each machine, so that one could compare not merely the percentage of each constituent part of the machines, but also the total resistances of the machines as a whole.

He was glad that Mr. North had emphasised the value of Professor Jones' paper, because that paper had given us all a good deal to think about in the direction of improving aeroplanes, and well merited the study of all interested in aircraft design. It would be interesting if Mr. North would indicate in what

way he thought improvement would take place. With regard to testing, he said that Mr. North tested each part on quarter-scale models, and then built up the complete model. He asked whether, in taking a small portion of the body and representing it in some way so as to get more accurate results, Mr. North obtained the actual resistance of that part of the body from his quarter-scale result, then incorporated the best result he had got into the complete model, and then tested the model as a whole, because if, owing to the question of similarity, these other parts would not be accurately measured in the complete model, it did not appear to be worth while going to such a degree of refinement in the complete model.

Finally, Mr. Handley Page referred to what he called a somewhat *ex cathedra* statement in the paper, that "There is little improvement to be expected in aerofoil performance, even by the use of slots." He recalled a statement he had heard made in 1918 or 1919, that R.A.F. 15 represented probably the best example of an aeroplane wing we were likely to attain and that there was little to be gained by wing research. Perhaps at some future date Mr. North's statement with regard to slots might be quoted against him in a similar way.

Major Low: Prandtl had recently published a wide range of experimental work showing that obstructions on the top of a wing promoted instability of the streamline flow over the back of the wing at a comparatively early stage. There then occurred the "breaking away" of the flow from part of the wing—a rather unhappy expression—and that part stalled; so that an obstruction, such as a strut base or bracing, on the upper side of the wing might be expected to promote turbulence and stalling over a strip of the wing corresponding to the breadth of the disturbance. This explanation did in a sense confirm Mr. North's view of the result as a reduction of the effective aspect ratio. With regard to skin friction and to the increasing resistance with increasing Reynolds' numbers, that again was a quite definite instability effect, according to Prandtl and v. Kármán. At very low Reynolds' numbers there was laminar flow over the whole of the wing, and it was a well known hydrodynamic principle that steady laminar flow gave the least resistance for a given stream velocity.

As the Reynolds' numbers increased, turbulence set in, first near the trailing edge of the wing, and then farther and farther forward towards the nose. At ordinary flying speed part of the flow might still be laminar, with a low contribution to resistance, and the remaining part of the flow turbulent, with a high contribution to resistance. With increasing speed the coefficient of drag would then increase as the turbulent region spread forward. The flow on the lower side was much less sensitive so that the interplane bracing produced most of this adverse effect on the lower wing. The addition of the top wing therefore might reduce the relative effect to less than half, but there was no evidence that the upper wing actually benefited aerodynamically. With regard to the statement that a 10 per cent. reduction in the total drag would make a difference of only about 2½ per cent. on top speed, Dr. Coales had pointed out that the speed would actually be increased 10 per cent. Mr. North clearly meant the total drag *coefficient*, and in that case he agreed with Mr. McKinnon Wood that the difference in speed should be 3⅓ per cent.

(*Added in writing.*) He had read Captain Sayers' note in *The Aeroplane* with attention when it first appeared and agreed with his suggestion that in the past a great deal had been lumped under "scale effect" which was now susceptible of more detailed analysis. He need not refer to channel wall interference as that was largely a *chose jugée*, but remaining discrepancies invited special attention as the lecturer, indeed, had insisted, rather than a drastic ironing out into "smoothed" curves.

Mr. Laurence Wingfield: The dominant impression which the paper had given him was one of pessimism, notwithstanding that Mr. North, in his con-

cluding paragraph, with the somewhat half-hearted analogy of an athlete, urged designers to further efforts in the direction of improving technique. There had been indicated in the paper the immense difficulties still to be overcome, and it was stated that, technically speaking, metal construction had realised all the structural economies to be expected of it. With regard to the problem of making an aeroplane without an undercarriage, and of making an aeroplane, mechanically launched, able to land safely with a landing gear which in flight would offer practically no resistance, he asked if Mr. North would give some indication of what would be the best solution. Also, he asked what information there was available to support the contention that a wing constructed without external bracing suffered as much loss on profile drag as was saved by eliminating the struts and wires.

Mr. E. F. SPANNER: He was particularly interested in the reference made by Mr. North to the undercarriage problem. From a detached point of view, he had continually found a survey of what is being done by aircraft designers leading him to wonder why more effort was not being made to develop simpler and more expeditious methods of "getting off." The problem would be of tremendous importance in any future conflict.

Developments along the line of catapults or taut wires for launching might well result in the virtual elimination of the undercarriage and improvement in performance in the air.

REPLY TO DISCUSSION

Mr. J. D. NORTH: He was very glad that the Director of Aeronautical Research had emphasised the important results which can be obtained and have been obtained by systematical wind channel work. All would be very glad to hear that, in addition to the compressed air tunnel, it was likely there would be a large diameter channel in which complete fuselages could be introduced. In view of the amount of information which should be able to be obtained, the construction of such a channel should be a sound economic proposition. Like Major Bumpus, he was surprised that the resistance of the "Crusader" with its radial engine should have been shown by wind tunnel tests to be little different from the water-cooled engined machine. It would be interesting to know if there is any reason to expect from such full-scale trials as were carried out, that these results would be confirmed on full scale.

Mr. Wimperis asks finally what precautions should be taken to ensure that the large wind channel should be used to fullest advantage, and if experiments would determine all the problems that I have in mind. The cone wind channel would certainly go a very long way to solving these problems, and one would suggest that the best way to ensure that it is used to the fullest advantage is to invite the co-operation of aircraft designers in advising on the work of the channel, always provided of course that the freest possible exchange of information is made all round.

"Affine" ordinarily means related, and is used to qualify aerofoils belonging to a family. In the United States it has commonly been used for aerofoils of a family obtained by varying the ratio of the horizontal and vertical ordinates of the profile.

In answer to Captain Sayers, one has since had an opportunity of looking up the reference he quotes, and one agrees that the priority he claims is established. One is not able to go so far as he does in including all interference effects under the term "induced interference." One would suggest as a definition of induced interference, that class of interference which can be expressed as an apparent change of aspect ratio. Captain Sayers points out that certain induced resistances might have normal components of opposite sign, but one does not

think that this is adequate to explain all classes of interference, many of which are obviously due to turbulence, as distinct from modification of the vortex system.

One entirely agrees with Mr. McKinnon Wood that the art of design is the art of seeing things as a whole, but technique is after all only a part of the apparatus of design. What Mr. Wood says about the pseudo-scientific habit of mind is particularly appreciated. It is only too true that, to paraphrase a well-known saying, "Some people become inebriated with the erudition of their technology." All scientific work requires the utmost scrutiny and criticism and aeronautical research has something to learn from medical research in this respect.

Mr. McKinnon Wood draws attention to the difficulty of deciding between the pursuit of a rigid systematic line of research and the continually turning aside to have a thorough look at novelties as one goes along. Both may lead to useful results, and in the end it all comes down to a question of time and money. The illustration which he gives of the importance of accurate representation in the case of the aeroplane wheel is a very excellent one. One must apologise for the arithmetical slip, $3\frac{1}{4}$ per cent. is of course of the right order and the text has been amended accordingly.

Major Bumpus is particularly interested in knowing how to get away from turbulence resistance. The answer of course is, construct an aeroplane entirely of streamline forms so mutually arranged as to avoid interference. This, obviously, is inconsistent with certain present day ideas of what is necessary from an operational point of view, and is particularly hindered by arrangements for cooling engines. One must therefore first do away with turbulences due to engine cooling, and secondly reconsider one's ideas of operational requirements, so as to allow a nearer approach to the ideal. Provided the problem is approached with an open mind, the solution, or at least a partial solution, should be within one's power.

In reply to Mr. Handley Page, one is sorry that he has been misled by the wording of the paper. The point with regard to external bracing and profile drag was meant to apply to the main planes as well as to the tail plane.

Mr. Handley Page's statement that one cannot take full advantage of what might be the best arrangement aerodynamically is of course one of the reasons why large turbulence drags at present exist. The various tables given in the paper are intended to be illustrative of the general tendencies rather than to have a precise qualitative significance. However interesting the more detailed figures to which Mr. Handley Page refers might be for other purposes, they are hardly necessary to the purpose of the paper.

In regard to his question on wind channel work, the point was that on the complete model, parts were put on which do give aerodynamical similarity though not geometrical similarity and the larger models are necessary to find what are appropriate forms for the smaller.

Mr. Handley Page does not definitely disagree with my statement that, subject to the qualifications of the paragraph which preceded it, there is little improvement to be expected in aerofoil performance even by the use of slots. If some people in 1918 were suggesting that R.A.F. 15 was the best example of an aeroplane wing likely to be maintained, others were equally talking about wings with values of L/D of 100. At least the vortex theory of aerofoils enables one to consider the matter with some degree of confidence and accuracy. One must come to the conclusion that the former prophets were more nearly right than the latter. There is one peculiar point about slots, they are purely devices for reducing profile drag. The machines *par excellence* on which the reduction of profile drag is of prime importance are racing aeroplanes. If slots will not improve the performance of a racing aeroplane they certainly will not improve the performance of anything else. It is to be hoped, therefore, that Mr. Handley

Page will arrange to enter a slotted machine for the next Schneider competition. It is of course understood that one is merely talking about the effect of slots on performance in the ordinary sense of the word, not on the possibility of reducing landing speed or the use of slots for improving slow speed control. It is possible that at some future date the statement made in the lecture with regard to slots may be quoted against one. Several years ago when the slots were first introduced to the public, remarkable claims were made as to what effect the slot would have on aeroplane design. One would rather have to father the present statement as to the limitations of slots than the exaggerated claims which were then made for it. Notwithstanding the importance of appreciating the limitations of this device, one still feels that it is the only important aerodynamical invention of the decade, and if it is disappointing that more use of it has not yet been made to improve wing sections, at least one is happy to think that it is fulfilling an important function in saving pilots from one of the commonest types of accident.

Major Low gives interesting and useful explanations of certain of the experimental results quoted in the paper. Everyone must be very grateful to Major Low for the work which he did in putting the work of Prandtl and others before British designers. With regard to what he says as to skin friction and to the increasing resistance with increasing Reynolds' numbers, one would have thought that the experimental figures quoted were rather outside the range of laminar flow. He would be very glad if Major Low could give some more information on the subject of critical speeds for streamline forms; also would the effects to which he refers still be present in the absence of circulation? It is particularly appreciated what Major Low says about the drastic ironing out into smoothed curves. Any experimental evidence worth having ought to contain genuine experimental observations. This particularly applies to full-scale testing.

The first part of Mr. Wingfield's contribution to the discussion appears to be a review of the paper as he understands it. The only thing which one need say about it is that facing facts is not pessimism. It is not possible to say anything more on the subject of an aeroplane without an undercarriage as even if one had reached a solution of this problem one should hardly be in a position to publish it.

The information in support of the contention that a wing constructed without external bracing suffers as much loss on profile drag as it to be saved by eliminating the struts and wires, is to be found in any reliable sources of aerodynamical information, and, one believes, is not disputed by those who manufacture "cantilever" machines. A simpler and more obvious illustration may be given. The resistance of the wings of the racing aeroplane is almost entirely profile drag; the problem of "cantilever" construction is at its simplest by reason of the small span for the weight carried; nevertheless the world's speed records are held by machines with externally braced wings, notwithstanding the fact that at least one of the designers has previously tried the "cantilever" wing. If there were an advantage in doing away with external bracing on aerodynamic grounds, it would be most noticeable on this class of aeroplane.

In reply to Mr. Spanner, the development of catapult launching is one possible means of progress. One is not acquainted with his system for "getting off" from taut wires and one is therefore not able to comment on it.

Captain ACLAND proposed a vote of thanks to Mr. North for his paper. He also took the opportunity to pay a tribute to the President, Colonel the Master of Sempill, and said the members should congratulate themselves upon his election to the Presidency, because ever since he had taken an active part in the affairs of the Society it had forged ahead rapidly.

PROCEEDINGS

SECOND MEETING, FIRST HALF, 64TH SESSION

In the Chair: THE PRESIDENT, COLONEL THE MASTER OF SEMPILL

THE USE OF LIGHT ALLOYS IN AIRCRAFT FROM THE POINT OF VIEW OF CORROSION

BY

H. SUTTON, M.Sc., Associate Fellow

A meeting of the Royal Aeronautical Society was held in the rooms of the Royal Society of Arts, John Street, Adelphi, London, W.C.2, on Thursday, October 18th.

The PRESIDENT (Colonel the Master of Sempill): Dr. Schutte, the President of the German Aeronautical Society, had stated that his Council had scanned the list of lectures to be delivered to the Royal Aeronautical Society during the present session, and had come to the conclusion that Mr. Sutton's lecture was from their point of view one of the most interesting. That indicated how very closely they were following the Society's work, and how extremely interested they were in the problem of corrosion. Having in view the increasing popularity in this country of marine type aircraft, the investigations of light alloys assumed ever greater importance than previously, if that were possible.

He was sorry to be compelled to leave the meeting early in order to represent the Society at a function of the Institution of Mechanical Engineers, and he asked Mr. Pye (Deputy Director of Scientific Research), Air Ministry, acting for Major H. E. Wimperis (Director of Scientific Research), to preside.

Mr. PYE: Mr. Sutton was at present the Head of the Metallurgical Section at the Royal Aircraft Establishment, and had been responsible for a great deal of work in connection with the prevention of corrosion of materials used in aircraft. With regard to the anodic oxidation process, he said that Mr. Sutton had modestly referred to it in the paper as being due to Bengough and Stuart. Much depended, however, upon the sense in which the word "due" was used. Was a chicken "due" to the hen that laid the egg or to the hen that hatched it? Certainly the latter's part was no unimportant one. Messrs. Bengough and Stuart had carried out the original research work in the laboratory, and all honour to them, but it was only fair to add that Mr. Sutton had developed it into a practical and effective method of protecting the materials used in aircraft from corrosion, and its success might be said to be due in very large measure to his work.

Mr. SUTTON: The careful selection of materials and the utilisation of the best workmanship in the production and application of materials is ultimately the most economical procedure in aircraft engineering. In no other forms of engineering construction is the call for efficient materials and skilful engineering so rigorous. The subject of the development of aircraft materials has been ably treated in the papers by Mr. J. D. North and Dr. Aitchison, read before this Society in

1924, and Colonel Belaiew has given us a useful discourse on the relative merits of steel and light alloys as materials for aircraft construction. The suggestion of the Council that this paper should deal principally with the question of corrosion of light alloys is perhaps an indication of the general interest in the subject at the present time.

Aluminium and Aluminium Alloys

During the past few years aluminium and aluminium alloys have found increasing application in the construction of aircraft. As with other new materials, the incorporation of these metals could only take place by the gradual process of eliminating prejudices, with which, as Mr. North mentioned, engi-

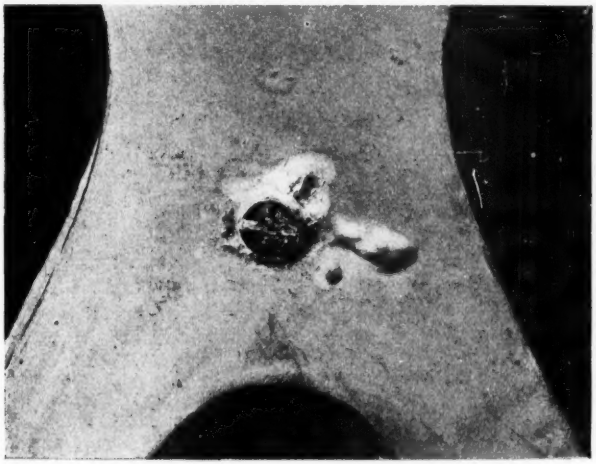


FIG. 1.

Corrosion of anodised aluminium at a brass bolt.

neering caution so often surrounds its designs. Their present position of importance has been attained by careful study of the causes of the failures experienced in their early use and by the practical application of the results of observations and investigations.

Commercially Pure Aluminium

The general extension in the application of aluminium to the requirements of every-day life has brought all of us into much closer acquaintance with the general properties of the metal.

It is well known that when the metal is stored in a comparatively dry and clean atmosphere it may be kept over relatively long periods of time without undergoing any apparent change. Under other conditions, however, notably in contact with solutions of salts, moisture, etc., it tends to corrode, and under certain conditions the rate of corrosion is very rapid. It has long been assumed that the resistance of aluminium to corrosion was due to the formation of a dense natural scale of oxide or hydroxide of aluminium on the surface of the metal by contact with the atmosphere. That this is actually the case, appears now to have been established beyond doubt. The film has been isolated by treatment of freshly cut strips of the metal in a stream of dry hydrogen chloride

gas, which attacks the aluminium from the cut edges, removing it as chloride and leaving the natural scale and certain impurities in the metal as a residue.[1] The rate of formation of the film has been studied by Vernon by determining the increase in weight of cleaned pieces of aluminium on standing in air.[2] Aluminium

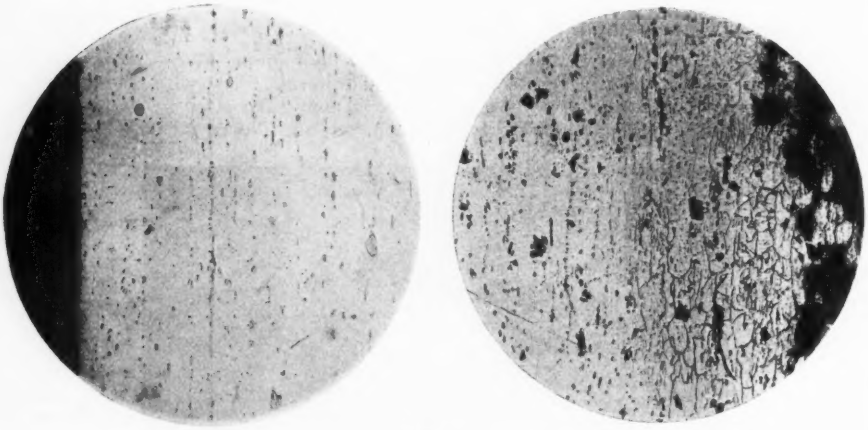


FIG 2.
Unetched sections of duralumin channel at uncorroded and corroded parts (× 100).

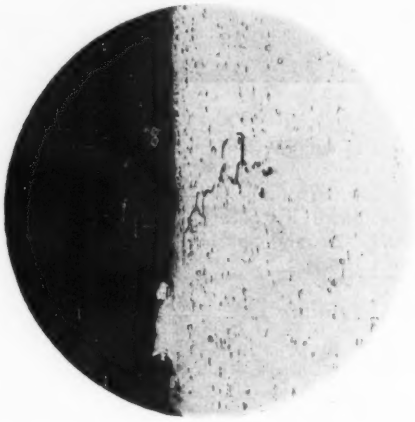


FIG. 3.
Section of duralumin sheet showing local intercrystalline corrosion, unetched (× 100).

is a metal which stands high in the electro-chemical series of elements und under appropriate conditions shows corresponding chemical activity. The dense natural film of oxide on its surface prevents the rapid combination of aluminium with the oxygen of the air. Under normal conditions the scale is very adherent, but

when wetted and dried repeatedly it tends to crack and to detach itself locally from the underlying metal. The researches of Bengough[3] and Evans[4] have thrown much light on the corrosion of aluminium and to them is due much of our present knowledge of the mechanism of the reactions which occur.

It is generally recognised that chlorides are a very common and a very potent cause of corrosion of metals and alloys. When aluminium comes into contact with sea water it is liable to be attacked, and the attack is liable to be concentrated at points where, in due course, deep pits are formed. At these places the chlorine ions coming into contact with the aluminium form aluminium chloride which, in contact with water, hydrolyses, forming aluminium hydroxide

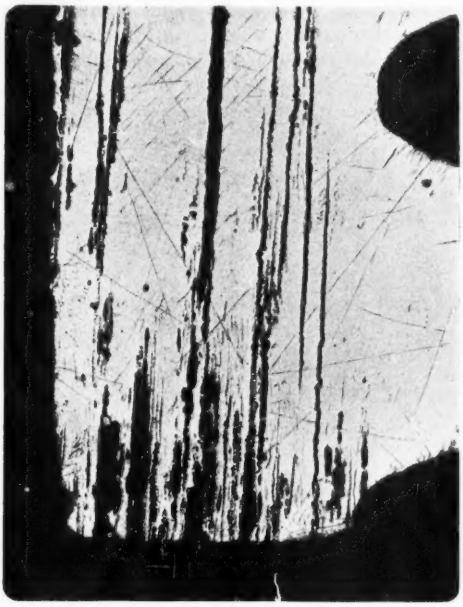


FIG. 4.
Section of duralumin fitting showing corrosion along laminations, unetched (×35). (*See also Fig.* 17.)

and hydrochloric acid. The hydrochloric acid reacts with further quantities of aluminium and in this way a cycle of reactions is maintained, by which a small amount of chloride can cause the corrosion of a relatively large amount of aluminium. Another factor, the importance of which has been demonstrated by Evans, is that of "differential aeration." The effect of restricted access of oxygen to a particular part of a piece of metal is to concentrate the corrosion in that area. To this fact a good many of the difficulties experienced in the use of aluminium are due.

The possible effects of chlorides on aluminium and other metals used in aircraft are of perhaps greater importance in this country than in most, on account of the extent to which our aircraft have to operate in coastal districts and over the sea. In the case of aircraft for some of the trans-continental routes of Europe and America the problem of corrosion prevention of aircraft parts is not such a serious one.

Commercially pure aluminium has found only restricted use in aircraft on account of its relatively low strength compared with that of aluminium alloys. On account of its useful working properties, notably its capacity to undergo deformation, it has been used for engine cowlings, fuel tanks, petrol and oil pipes, instrument cases, pitot tubes and other parts. With all these parts troubles have occurred by reason of corrosion occurring in service. In the days of the early use of aluminium in aircraft, contact with other metals was a frequent source of trouble. In a few cases in which copper rivets had been used, serious corrosion of the aluminium occurred, as might be expected, on account of the highly electro-positive nature of aluminium. Corrosion commencing at the junction of the two metals has been observed not infrequently to spread internally in aluminium sheet, causing long blisters to radiate from the seat of corrosion (Fig. 1). Contact with other copper alloys, *e.g.*, brasses and bronzes, is almost as bad as with copper. Where such contacts cannot conveniently be avoided

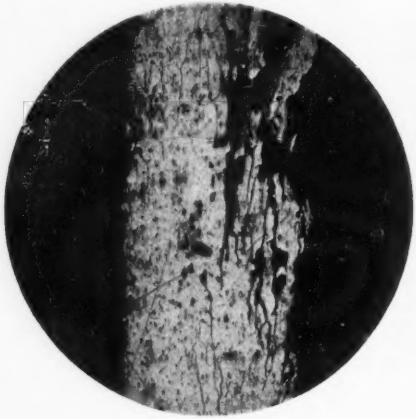


FIG. 5.

Section of nickel-plated duralumin showing intercrystalline corrosion, unetched (× 30).

it has been found beneficial to zinc-plate the copper, or copper alloy, thus bringing into contact aluminium and zinc, which are metals standing in close proximity in the electro-chemical series and between which there is therefore little tendency for electro-chemical action. Contact of pieces of aluminium with steel usually results in accelerated corrosion of the steel, but the non-corrosive steels of the types at present in use appear to be capable of successful use in contact with aluminium and aluminium alloys.

Although a number of solders are known with which aluminium can be soldered effectively, the use of solders for joining aluminium has been restricted by the relatively poor resistance to corrosion of the soldered joints. In general, the life of soldered joints in aluminium is short if they are exposed to corrosive agencies. Welding has proved a more suitable means of securing tight joints for such parts as fuel tanks, and the art of welding aluminium in the aircraft industry has attained a very high standard. When suitably produced, the welds are relatively sound and much more serviceable than soldered joints. As the added metal is practically the same as the rest, there is no marked tendency for corrosion such as occurs with solders. There is, however, a tendency for particles of flux to remain in the joint and round about it. Fluorides and chlorides, the

main constituents of the fluxes used, are very corrosive and serious corrosion may occur unless care be taken to remove residues of flux by thorough washing.

Duralumin

It is now well known that duralumin is liable to corrode on prolonged exposure to the atmosphere or other corrosive agency and undergoes serious corrosion under the influence of sea water or marine conditions. Corrosion of duralumin is frequently accompanied by the formation of a deposit on the surface of the metal, and of pits or craters. Fig. 7 shows a corrosion effect in duralumin channel. The reactions occurring appear to be similar to those observed with commercially pure aluminium and the effects of seams, close joints, and contact with other substances are as serious as with aluminium. Fig. 8 shows corrosion of a duralumin plate in contact with wood.

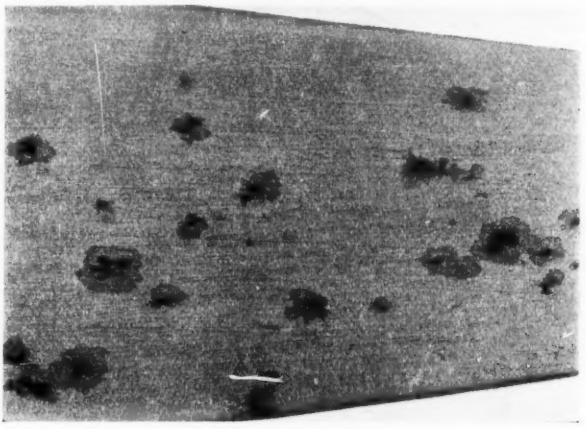


FIG. 6.

Magnesium forging corroded at inclusions of oxides, flux, etc., during storage indoors (slightly enlarged).

In the case of duralumin and certain other wrought alloys there is a marked tendency for corrosion of the intercrystalline type to occur, the corrosion penetrating the metal along the boundaries of the crystals and not necessarily effecting substantial change of the appearance of the surface of the metal. Fig. 2 shows two photomicrographs of sections from the same duralumin member. In the one section the normal structure at an uncorroded part is shown, and in the other the structure at a part which has been attacked by intercrystalline corrosion. Both the photomicrographs represent the structure of the unetched sections. Intercrystalline corrosion frequently commences at isolated points, and such a case is illustrated by the photomicrograph shown in Fig. 3. The section was taken from a duralumin sheet which showed indications of corrosion in the form of small pustules of aluminium hydroxide some time after anodic oxidation. It was found that intercrystalline corrosion had started during storage of the original sheet, and during subsequent exposure of the anodically-treated sheet to marine conditions intercrystalline corrosion had continued. In certain cases, notably in samples exposed to the atmosphere over long periods, intercrystalline corrosion occurs, but there is no corrosion at the surface apparent to the unaided eye. The intercrystalline type of corrosion is accompanied by marked decrease

in mechanical properties. In the early stages the elongation values show a marked decrease. As the corrosion progresses the static tensile strength is reduced substantially. The tendency to intercrystalline corrosion appears to be affected by the nature of the heat treatment and subsequent working of the duralumin. Duralumin softened by heating to 360-380°C. is very susceptible to intercrystalline attack. The tendency appears to be greater in material of light gauge than in heavy. It is greater in material quenched in hot water than in that quenched in cold water in the final heat treatment, and increases as the temperature of ageing is raised. Under some conditions the influence of deformation, subsequent to final heat treatment and ageing, is very marked, *e.g.*, deformation of heat treated and aged material by tension or bending has been found to increase the tendency to intercrystalline corrosion. The surface of the

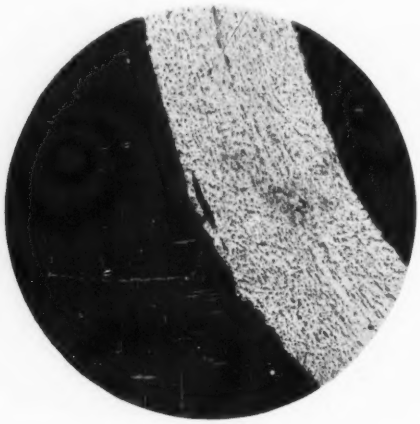


FIG. 7.

Section showing blister in duralumin channel caused by corrosion (× 20).

metal has been found to be influential, sand-blasted surfaces showing an increased tendency compared with polished surfaces, or with the natural surface resulting from rolling and heat treatment. Some interesting reports by H. S. Rawdon dealing with experiments on and experience of intercrystalline corrosion have been published recently in America.[5]

Fig. 10 shows intercrystalline corrosion of duralumin plate from a flying boat and Fig. 19 shows penetration of molten lead into duralumin which occurs along the crystal boundaries also.

A defect frequently observed in duralumin takes the form of longitudinal streaks of oxides and foreign matter in the metal. In the processes of forging, rolling and extrusion, inclusions in the metal are elongated and then give rise to the well-known laminations in sheet and discontinuities in bar. These are usually shown, if present in appreciable amount, by bend tests or the "nicked bar" tests, appearing plainly on the fractured surfaces. (See Figs. 11 and 12.) The streaks form a very easy channel for the penetration of corrosion, as shown in Fig. 4, which shows a section taken from a duralumin water pipe connection, and also in Fig. 9. The manner in which the corrosion has penetrated along the streaks is typical of a number of similar cases which have come to the author's notice. The streaks are also detrimental to the metal in other respects.

On the leading edge of duralumin airscrews of marine aircraft pitting has been observed to occur near the tips of the blades, but this appears to be due to erosion of the metal by impact at high velocity with sea water. (See Fig. 18.)

Aluminium-Copper--Silicon Alloys

An alloy containing approximately 4 per cent. copper and 2 per cent. silicon possesses excellent forging, rolling and other working properties, and mechanical properties which approach closely, but generally do not equal those of duralumin. A similar alloy containing 4-5 per cent. copper, 1 per cent. silicon and small quantities of iron and manganese can be heat treated to give properties in sheet, bars and forgings equal to those of duralumin. Both these alloys have been found to be more susceptible to intercrystalline corrosion in the heat treated and aged condition than normal duralumin. (See Fig. 13.)

FIG. 8.

Corrosion of duralumin plate in contact with wood (× 1).

Aluminium-Silicon Alloys (Wrought)

Binary alloys of aluminium and silicon can be worked by extrusion, forging and rolling, but although stronger than commercially pure aluminium, have not so far been produced with properties comparing favourably with those of duralumin. The corrosion resisting properties of the 11-13 per cent. silicon alloy in the wrought condition have not been found to be so good as those of normal duralumin.

Aluminium-Copper-Nickel Alloys (Wrought)

"Y" alloy, developed by the National Physical Laboratory, has proved capable of rolling and forging and can be heat treated to give properties

practically equal to those of duralumin. This alloy, though subject to intercrystalline corrosion under certain conditions, has been found to show considerable resistance to corrosion. Another alloy, containing 2-3 per cent. of both copper and nickel, while not so strong as duralumin, possesses similar working properties and moderate resistance to corrosion. This alloy also is susceptible to intercrystalline corrosion.

Aluminium Casting Alloys

Of the aluminium casting alloys used in aircraft construction in this country the 11-13 per cent. silicon alloy is probably the most resistant to corrosion, followed closely by "Y" alloy and L.11 alloy. Normally the cast alloys do not undergo intercrystalline corrosion, but cases of this have been observed. Fig. 14 shows corrosion within the crystal grains sometimes observed in certain cast alloys.

FIG. 9.
Section showing corrosion of laminated duralumin (× 100).

Protection of Aluminium and Aluminium Alloys

Experience has shown that even the most resistant aluminium alloys corrode to an appreciable extent under conditions met with in aircraft, and it is necessary to employ means of protection in order to secure the desired life of parts made in light alloys.

Enamels, paints and varnishes have been found to be capable of affording considerable protection except under the severest conditions. The best results have been obtained with pigmented oil varnishes of both the linseed oil and tung oil types, and also with cellulose enamels. Under certain conditions the adhesion is liable to be low, but when the metal parts can be sand-blasted no trouble is experienced from this cause.

Asphaltum paints have been used with success, but these are normally rather soft and the coatings are easily damaged. Stoving enamels have been used with some success on parts made in light alloys, but in certain instances troubles have been experienced due to the elevated temperatures employed in the stoving operation (about 170°C.). Parts in light alloys machined to close limits should not be stove enamelled as the temperatures employed are sufficiently high to cause distortion and slight permanent changes of dimensions.

In general, opaque coatings prove more protective than transparent, and it is of interest to note that corrosion of aluminium alloys has been observed to be accelerated by light in laboratory experiments. Exposure to tropical temperatures renders some enamels very brittle.

With organic protectives of this class the risk of damage to the coating is always present and corrosion at damaged places may become serious. It appears to be desirable not to allow the coating of enamel to become very thick as the degree of protection is then lessened. It is probable that most enamels are capable of absorbing moisture and, if present in considerable amount, can convey to the metal sufficient moisture to maintain the progress of corrosion.

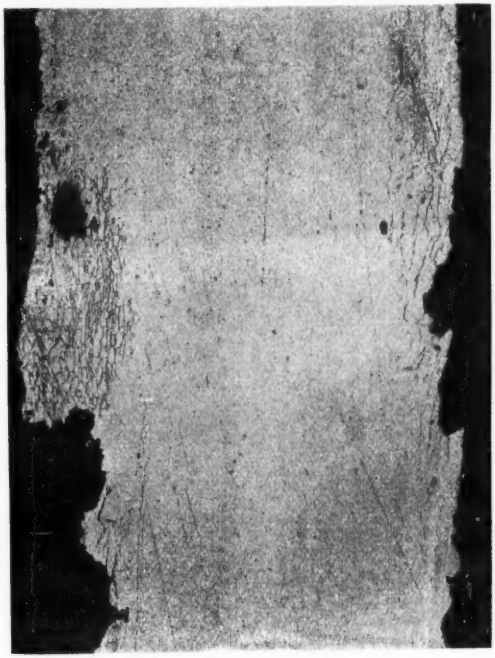


FIG. 10.

Section showing intercrystalline corrosion of duralumin plate from a flying boat hull (× 30).

A process which has been found capable of affording considerable protection to aluminium alloys against corrosion is that of anodic oxidation, due to Bengough and Stuart.[6] The process consists in making the article to be treated the anode in a bath of aqueous chromic acid and gradually raising the voltage from 0-50 over a period of one hour. As a result of the treatment, aluminium receives a film of oxide,[7 8] approximately one hundred times thicker than the natural oxide film which forms on prolonged standing in the atmosphere.[9] The protective effect of the treatment is very much improved by greasing the film, and lanolin has proved a suitable substance for this purpose. The ungreased film also forms a suitable basis for paints and enamels, the combined treatments affording excellent protection. The nature of the process is such that parts of

irregular shape receive a coating, the "throwing power" being better than that of the best plating baths. Certain aluminium casting alloys, notably alloys containing more than 5 per cent. of copper cannot be treated by the process nor can parts in contact with steel, iron, copper or brass. During the past

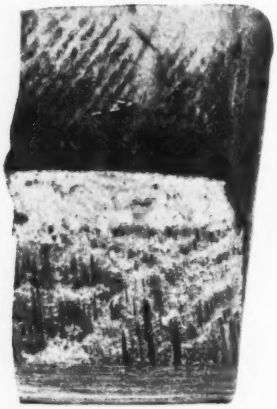


FIG. 11.

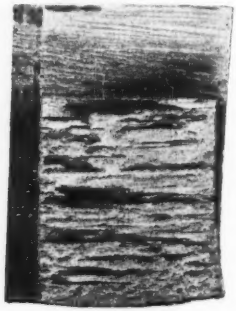


FIG. 12.

Fractures of duralumin forging showing laminations (×2).

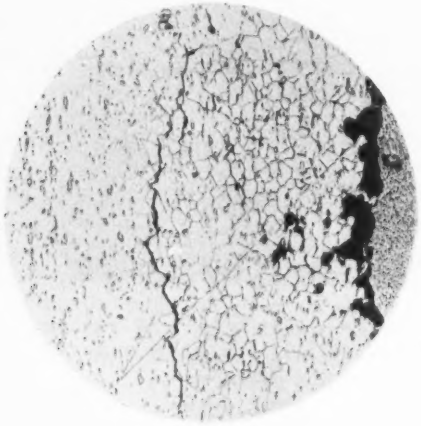


FIG. 13.

Section showing intercrystalline corrosion of "Lautal" alloy (×100).

five years the process has passed from the laboratory stage to full-scale practical operation, and the results of practical tests have shown that the protection afforded is considerable, even when the conditions of use are severe. Anodic oxidation does not prevent barnacles and other marine growths from attaching themselves to aluminium immersed in the sea, but probably hinders attack on the metal.

Nickel coatings have frequently been applied to aluminium and aluminium alloys by electro-deposition processes, by which it is possible to produce what appear to be serviceable and adherent coatings. Owing, however, to the electro-negative nature of nickel with respect to aluminium, the latter is seriously attacked at points where the two metals in contact are subjected to the influence of a corroding medium. Electro deposits of nickel and other metals are usually porous to some extent and with deposits up to 0.001in. thick it has been found practically impossible to secure sufficient freedom from porosity to secure complete isolation of the underlying aluminium from corrosive agencies. The progress of corrosion is actually hastened by the presence of nickel, which remains unattacked. At the junction of the metals the corrosion tends to spread very quickly, causing the two metals to separate. In order to secure adequate protection over long periods, heavy deposits appear at present to be necessary and the weight of such deposits would be disadvantageous in aircraft. Fig. 5 shows a photomicrograph of nickel plated duralumin sheet which has corroded on exposure to marine conditions in an aircraft. Although the duralumin was at the time of the examination completely penetrated by intercrystalline corrosion, the nickel was still adherent in parts and practically uncorroded.

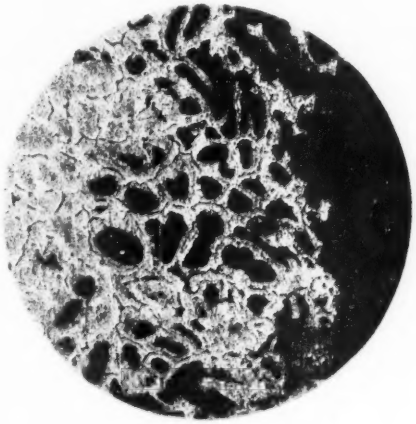


FIG. 14.

Section showing intradendritic corrosion of cast aluminium alloy (× 100).

Electro-deposited coatings of zinc have been found to afford considerable protection to aluminium and its alloys. With suitable plating baths it has been found possible to produce[8] satisfactory deposits on aluminium and the aluminium alloys commonly used in aircraft construction. Deposits 0.0005in. thick exert considerable protective effect and the weight of the coating is sufficiently low as not to preclude the possibility of using this means of protection. Owing to the fact that zinc stands close to aluminium in the electro-chemical series there is very little tendency, if any, for the zinc coating to stimulate corrosion of the underlying metal.

Cadmium electro-deposits have proved capable of protecting most of the alloys[8] of aluminium, but have so far not proved very successful on aluminium. On the copper alloys in particular, deposits 0.0005in. thick have been found to afford excellent protection. At present, protection of aluminium by zinc and cadmium has not been carried substantially beyond the laboratory stage, but

both methods appear to promise successful results if further developed. The weight of 0.0005in. of zinc or cadmium, 0.6-0.74 oz./sq. ft. is of the order of that of coatings of paint and enamel sometimes employed.

A form of protection of duralumin recently developed in America consists of a coating of aluminium of very high purity. The metal is produced in such a way that there is no surface of separation between the outer layer of pure aluminium and the core of duralumin, but the two metals are to some extent inter-diffused. The coating has high corrosion resistance and, according to the claims of the makers, it protects the duralumin at cut edges owing to its electrode potential being more negative than that of the duralumin. If in practical applications the material behaves in the way indicated by laboratory tests, it appears likely that reasonable resistance to corrosion should be obtained.

FIG. 15.

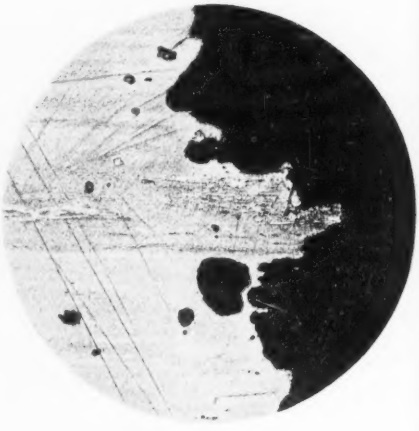


FIG. 16.

Sections of corroded magnesium alloys showing mode of attack of sea water corrosion (×100).

Numerous attempts have been made to use sprayed metal coatings for the protection of aluminium, and some measure of success has been obtained. Coatings of aluminium, cadmium and zinc have been employed. The main disadvantages of this method lie in the difficulty in securing adequately uniform coatings when it is desired to keep the thickness as low as reasonably possible. Even the best sprayed coatings are somewhat porous and it is probable that coatings 0.002in. to 0.003in. thick are necessary in order to obtain satisfactory protection under relatively mild conditions.

In America a process, known as the Z.D. process, has been used with some success on aluminium casting alloys. It consists in soaking the castings in an aqueous solution of sodium silicate of specific gravity 1.1 and baking at temperatures in the range 120-175°C. The treatment minimises the effect of porosity of the castings.

A process known as the "Jirotka" process has been developed in Germany and this consists in immersing the articles in a hot solution containing chromates and salts of the heavy metals, whereby a film is produced on the surface of the aluminium or alloy. The films produced are very thin and appear likely to prove of greater value for decorative purposes than for protection against severe corrosive agencies.

Magnesium

Although magnesium has not yet been used extensively in aircraft construction, magnesium alloys are assuming increasing importance in the engineering world of to-day. The stronger magnesium alloys are finding application in the form of pistons, connecting rods and crankcases of internal combustion engines, and in Germany developments in the use of magnesium alloys in aircraft engines have been made. The general properties of magnesium and its alloys were described by Mr. W. R. D. Jones in a recent paper before this Society.[10]

It is now well known that the casting alloys of magnesium permit the production of castings equal to aluminium alloy castings as regards freedom from cavities, inclusions and similar defects.

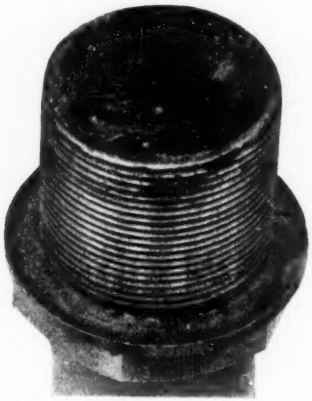


FIG. 17.

Corrosion of duralumin fitting originating from abrasion of the anodic film (×1).

The main obstacle to the use of magnesium alloys in the construction of aircraft is to be found in their relatively low resistance to corrosion, particularly under the influence of marine conditions. Magnesium and its alloys are vigorously attacked by sea water, much more rapidly than aluminium and its alloys. (See Figs. 15 and 16.) The attack very soon causes complete disintegration if allowed to continue. Under normal atmospheric conditions, the natural oxide film appears capable of affording sufficient protection for many purposes, but the effect of contact with other metals is liable to give rise to difficulties. Corrosion has frequently been observed from particles of slag, oxides and fluxes in the metal, and such inclusions are liable to set up corrosion of a serious nature even during storage of the metal under the most suitable conditions. (See Fig. 6.)

The problem of protection of magnesium against corrosion appears to be difficult of solution on account of the high electrode potential and chemical reactivity of the metal. One of the most promising lines of attack upon the problem is by alloying magnesium with other metals. In this connection, improvement has been attained in the corrosion resisting properties of casting alloys by the addition of manganese in amounts up to 0.4 per cent. Such additions have effected a marked improvement, although the corrosion properties of the alloys still fall far below those desired for successful use in aircraft.

Paints, enamels and varnishes of the types which have proved to be most suitable for the protection of aluminium and other metals are generally found to be quite ineffective on magnesium alloys as protective coatings against sea

water. The best results with this class of protective, so far obtained, have been with cellulose enamels, but the protection obtained is only moderate.

The anodic oxidation process, as applied to aluminium alloys, is unsuitable for the treatment of magnesium, but it appears possible that by a similar process, means of producing protective coatings on magnesium could be found.

Dipping processes, *e.g.*, immersion in 10-20 per cent. solution of sodium or potassium dichromate at 60-90°C., or in chromate solutions such as one containing 1 per cent. potassium dichromate, 1 per cent. potassium alum, 0.5 per cent. caustic soda, at 90-95°C., have been found to produce on magnesium and certain of its alloys thin films which certainly improve corrosion resistance, and which form a good basis for paints and enamels. At present such treatment

FIG. 18.
Pitting of the leading edge of a duralumin airscrew by sea water (× 2).

appears to be the best available for parts liable to be exposed to the influence of marine conditions and atmospheres. For use after the production of a protective film by one of the dipping processes, a cellulose enamel capable of leaving a dense, impermeable coating on the parts appears to give the best protection.

Fatigue Properties and Corrosion

The researches of Haigh[11] and Jenkin and Lehmann[12] in this country, and of D. J. McAdam, Jun.,[13] in America, on the influence of corrosion on the fatigue properties of metals, have introduced a subject of considerable interest and importance respecting the use of metals in aircraft. The more recent work of McAdam shows that the fatigue limit of metals is reduced in some cases to a value as low as one-third of the normal value by contact with a corroding medium. It appears to be the fact that the fatigue properties of metals are reduced immediately and substantially by corroding media. In a recent publication[14]

McAdam states that one hour's corrosion of unstressed aluminium reduces the fatigue limit by nearly one half, and one day's corrosion by more than one half. By contact with salt water the fatigue limits of aluminium and duralumin are reduced substantially. The properties of these materials as shown by the usual static tension tests are not influenced in this way.

At present the influence of protective coatings on the corrosion fatigue limits of light alloys is not known, but it is of interest to note that in the case of stainless steels, McAdam has found that for each increase in corrosion resistance by the addition of elements such as chromium there is an increase in corrosion fatigue limit. It appears likely, therefore, that the corrosion fatigue properties of other metals may be improved in a similar manner.

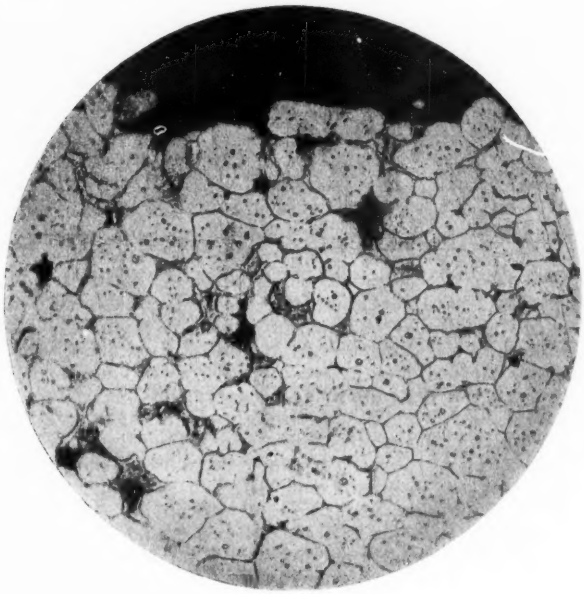


FIG. 19.

Section showing penetration of duralumin by molten lead (× 100).

The recent researches in this field indicate that for materials for aircraft construction consideration both of the ordinary corrosion properties and of the stability of the fatigue properties in the presence of corrosive media will be of importance, and that methods of protection will be judged according to their ability to stabilise the normal fatigue properties of the materials to which they are applied.

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Discussion

Mr. Pye: When looking at Mr. Sutton's slides illustrative of intercrystalline corrosion he had conjured up a mental picture of the Graf Zeppelin in mid-Atlantic, and of this subtle and insidious disease creeping into the very heart of the structure, and had felt that if he had to cross the Atlantic in an airship in the future, that vision would haunt his uneasy dreams. He hoped, however, that when that time came the workers on this subject would have scotched the devil of inter-crystalline corrosion. A point which had impressed him was the extraordinary difficulty of quantitative measurement of corrosion. In the attempt to develop quantitative methods, attention was necessarily fixed upon laboratory experiments, and in such experiments the natural tendency was to accelerate corrosion, *i.e.*, to subject the samples to very severe conditions. It was very important, however, that there should be maintained a proper balance between the laboratory experiment conditions and the conditions in actual service. He had in mind some specimens of magnesium alloy which were subjected to laboratory tests, and of which very little remained after a fortnight; but he also remembered having seen a crankcase cast in a magnesium alloy, which was said to have been in use on a seaplane during 500 hours of flying, and on which, to his untutored eye, there was not a sign of corrosion. That was perhaps an extreme example, but the point was worth bearing in mind. Mr. Sutton's results showing the effect of corrosion on fatigue limit stress were of incalculable importance, because, as was pointed out, not only might the effect of the corroding medium be quite invisible on the surface of the material, but the properties of the material as determined by static tensile tests were also unaffected. In service the success or failure of a material might depend upon the fatigue limit stress, and the fatigue limit might be reduced rapidly to a value of something like one-third of the normal value by contact with a corroding medium.

Major Barlow: He would like to comment on the Chairman's statement that specimens of magnesium alloy which, when exposed under laboratory conditions, had practically disappeared in a few days, whereas a magnesium alloy crankcase had been used on a seaplane for weeks and had not shown signs of corrosion. He (the speaker) pointed out that in the latter case there were anti-corrosion influences; oil was deposited all over the crankcase in practice, whereas in laboratory tests it was not. In his experiments in the laboratory he submitted specimens to the usual salt spray night and day, and in addition he exposed specimens on a slipway, where they were subjected to the rise and fall of the tide

twice a day as well as to the drying effect of the wind. In comparing the results of the two sets of experiments he had found that he did obtain corrosion effects approximating to those experienced under service conditions. Referring to Mr. Sutton's remarks on the accelerated corrosion of steel when in contact with light alloys, and the photomicrographs illustrating that accelerated corrosion, he said that if some examples of the effect of anti-corrosion treatment had been given also, one would not be quite so alarmed. He asked for information as to the behaviour of cadmium-treated steel and anodically-treated duralumin, and said he understood that treatment of that nature was being applied to the structures of airships now being built in this country. With regard to the welding of aluminium, he said that after much experimenting he had found that the only solder which would withstand corrosion was one containing 30 per cent. of silver, which was a rather high percentage for practical purposes. Whilst agreeing that this welding was rather difficult, he said there was no reason why, if the flux were properly cleared away, a solder containing a certain percentage of silver should not be as anti-corrosive as the aluminium itself. Referring to the intercrystalline corrosion of a sheet of duralumin after anodic oxidation, mentioned in the paper, he said he had not experienced such corrosion, and it was probably due to improper storage. When storing light alloy sheets, one must always bear in mind the necessity for maintaining a proper temperature and for ensuring freedom from moisture. He had not found that in practice the aluminium-copper-silicon alloys were more susceptible to intercrystalline corrosion than normal duralumin, because these alloys had not the laminations present in duralumin, and consequently there did not exist in those alloys the long passages which were found to exist in duralumin, and along which the corrosion proceeded in the latter case. He believed it would be generally agreed that the use of paints and varnishes for the protection of light alloys was not a practical proposition, because they were scratched off in service, so that small pockets were formed, at which corrosion commenced. The United States Navy, he believed, had used with success a kind of rubbery paint on some hulls. He did not know its composition, but he suspected that it was something like the type of rubber used by submarine cable manufacturers, which rubber was not affected in any way by sea water; it was probably balata, or something of that nature. The nickel coating of duralumin was carried out, not with a view to affording protection against corrosion, but in order that sound ordinary soldered joints could be obtained when the material was used for making tanks. His experience with pure aluminium on light alloys had not been very successful; in tests inside and outside the laboratory no improvement had resulted; but in some cases the results were worse than those obtained before the treatment of the alloys. He agreed that, once we could protect magnesium against corrosion, the light alloy field would be opened up considerably. He had found that the magnesium castings were less susceptible to corrosion than were the rolled sheets, whereas with the ordinary light alloys the opposite was the case. With regard to Fig. 18, illustrating the pitting of the leading edge of a duralumin airscrew by sea water, he said it should be emphasised that that pitting was probably due to erosion and not to corrosion. Finally, Major Barlow expressed regret that the paper did not contain more information with regard to fatigue and corrosion, and also with regard to the fatigue of materials which had been treated with a view to preventing corrosion.

Mr. WALLIS: Of all the materials at the service of the designer perhaps the light alloy was the most " sympathetic " that one could use. Its comparative solidity and its comforting masses were very helpful to the designer in his work, and the mere dimensions of the pieces with which he was working enabled him to get out of many difficulties in design which were much more awkward to circumvent when dealing with other materials, such as high tensile steels. He would not venture to pose as an authority on corrosion, but

he had had practical experience of light alloys for over fifteen years, and during the whole of that time only two serious cases of corrosion had come under his immediate notice. The first was due to his own stupidity, when very young, in screwing a bronze fitting into an aluminium tank. The second case had occurred quite recently, due to a radiator manufacturer having screwed an aluminium alloy casting into a bronze radiator. Critics might point out to him that he was an airship constructor, and airships did not last long enough to corrode. He could cite instances, however, of airships which had lasted upwards of ten years in actual service, and the severest critic of airship constructors—even Mr. Spanner—would grant that at least they gave an airship plenty of time to corrode during construction.

Corrosion troubles might be classified under two heads:—

(1) Those which were brought about through faults of design and construction; and

(2) Those which arose during service and maintenance.

To take the second part first, perhaps it was because an airship was under construction for so long a period that the constructors took such pains to prevent corrosion, and the possibilities of surface corrosion did not alarm him to the same extent as Mr. Sutton's remarks with regard to the danger of intercrystalline corrosion. He ventured to disagree with Major Barlow in that the use of paints and varnishes for the protection of light alloys against corrosion was impracticable as airship constructors had been compelled to employ paints and varnishes for the prevention of surface corrosion, and they could fairly say that this means of protection did give reasonably good results. As an example, H.M.A. R.100 was now virtually complete, construction having occupied just over two years. During that time there had been consumed some 780 gallons of oleo resin varnish, costing £800 for material alone. The labour charges involved in the spreading of this large quantity of varnish over the surface of the structure amounted to upwards of £2,000. One might say, therefore, that whilst this structure was in the manufacturers' hands the charges incurred purely for the purpose of preventing corrosion amounted to over £1,000 per annum, and that figure served to emphasise the importance of evolving some more permanent means of dealing with surface corrosion. At the time that the construction of the R.100 was commenced the use of cellulose paints and enamels, he believed, was not an approved process, and the constructors were compelled to use an oleo resin varnish, but since that time cellulose enamels had been approved, and he fancied that these constituted a very great improvement on the varnishes which had been used on the R.100. They were much tougher, more difficult to scratch, and, provided the material to which they were applied was clean, they seemed to have good adhesion.

Mr. Sutton had also raised points under the first heading of considerable importance to the designer, as, for instance, questions of heat treatment, the annealing and normalising temperatures of duralumin, and their general effect on intercrystalline corrosion. In a report made by Professor Jenkin (Report of the Airworthiness of Airships Panel, R. & M. No. 970, App. II.) it was stated that "there is no evidence that intercrystalline corrosion has ever occurred without surface corrosion. . . ." On the other hand, Mr. Sutton had stated in his paper that in certain cases, notably in samples exposed to the atmosphere over long periods, intercrystalline corrosion occurred, but that there was no corrosion at the surface apparent to the unaided eye. Unless Mr. Sutton was postulating certain peculiar conditions differing from those considered by Prof. Jenkin, such as exposure to the atmosphere without protection for long periods, his statement appeared to cast some doubt on the statement contained in the report referred to, and further information on this point would be of great utility.

With regard to the susceptibility to intercrystalline corrosion of duralumin when softened by heating at the annealing temperature, he pointed out that no experienced constructor would leave this material in the annealed condition; consequently, intercrystalline corrosion was scarcely likely to arise from that cause.

Another point of considerable interest was that concerning the susceptibility to intercrystalline corrosion of material quenched in hot water, and of material which had been subjected to a fairly high temperature during ageing. Neither of these causes were operative in any well-regulated constructional works, but the further point that deformation after heat treatment might predispose the material to this form of corrosion was a very important one.

Constructors always tried to avoid the manipulation of sections after they had been finally heat-treated, but in dealing with very light braced structures in which rather flimsy sections were employed, it was often the intention of a designer to stabilise his sections by performing the final stamping or bending operation after the final heat treatment. Frequent examples were met of flimsy channels, pressed bracing pieces, and so forth, which, if heat-treated after the last press operation, would be so distorted by the immersion in the salt bath as to be unusable, and one might say that approximately 30 per cent. of the light alloy structure of a rigid airship was, and always had been, composed of pieces which had been subjected to this final press treatment. It was not his experience that such pieces showed a marked tendency to corrosion. Many such pieces in R.100 had been manufactured upwards of 2½ years, and had been lying in a wet, cold and draughty shed, but he ventured to suggest that in very few cases indeed would Mr. Sutton find any traces of corrosion whatever. Finally, Mr. Wallis said he did not think that in actual fact light alloys suffered quite so much from corrosion as the rather gruesome illustrations given in Mr. Sutton's very able paper would lead us to believe.

Dr. LESLIE AITCHISON: He suggested that the title of the paper should have been "The 'Mis-use' of Light Alloys in Aircraft," and that, in the absence of wholesome correctives such as those administered by the Chairman, Major Barlow and Mr. Wallis, the title of the next paper would be "The 'Dis-use' of Light Alloys in Aircraft." The majority of the illustrations which adorned the paper were of duralumin. At first he had wondered whether that particular selection had been made because duralumin corroded the most of all the light alloys, or because it was the one which was used most, but he ventured to think, since Mr. Sutton had pointed out that some of the other alloys corroded more than duralumin, that he had been led to cull his illustrations because duralumin was such an important material and was so widely employed in aircraft. It was necessary to point out, however, that although light alloys did corrode very considerably, nearly all other engineering materials corroded quite considerably too, and one was quite used to seeing rusty steel knocking about without being seriously concerned about it. Mr. Sutton was not seriously concerned, but some people were as soon as a light alloy began to corrode. Corrosion occurred in brass, and the corrosion of a radiator or of the homely furniture round about the hearth was at least as annoying as some of the examples brought forward by Mr. Sutton. The value of the paper would be considerably enhanced, he suggested, if Mr. Sutton would give some comparisons to show the relative behaviour of the different classes of metal. After all, he had dealt with the light alloys as a group, and the paper, as it stood, damned them fairly thoroughly; a much more accurate impression of the situation would be gleaned if he would give some comparative figures—not loss of weight figures, and things of that kind, but actual figures which had been determined during years of experience; such figures did exist. The value of the paper might be enhanced further if Mr. Sutton would disclose the conditions under which the various samples of light alloys had corroded, because one could always corrode a light alloy or any other metal,

and certain circumstances brought about more rapid corrosion than others. Some of the specimens might have been exposed for years, and others for quite a short time, and it would be an advantage to have the facts. Dealing more particularly with intercrystalline corrosion, principally because he considered that the remarks in the paper with regard to it were most startling, Dr. Aitchison said it should be realised very definitely that duralumin—and he was now speaking particularly about duralumin—did not corrode spontaneously; the material, as produced, did not contain the seeds of disintegration, as might be imagined from some of the remarks made in the course of the discussion. It was quite necessary, if corrosion were to occur, to expose the material to those conditions which excited corrosion. Intercrystalline corrosion, like all other forms, started from the surface of the material, and therefore he did not think the question was a metallurgical question; it was one entirely for the users of the material. A light alloy would, under certain conditions, corrode internally and externally if one allowed it to do so, but it was up to the user not to allow it, and if it were adequately protected it would not corrode in either way. The problem of intercrystalline corrosion was one to be solved, not by the metallurgist, but by the anodic oxidation expert or the paint and varnish producers. It would probably reassure the Chairman in regard to his future crossing of the Atlantic, and Mr. Wallis in regard to the immediate future of his airship, if he stated that in the course of a good many years of experience and observation of light alloys he had never known intercrystalline corrosion to occur in duralumin without there being some evidence on the surface. He had always been able to find some definite evidence on the surface of the metal where the corrosion had commenced, and, indeed, it seemed impossible to conceive that corrosion could have proceeded from the outside without leaving some evidence behind it; he was not prepared to believe that it did not start from the outside, and he did not think Mr. Sutton would ask him to believe it either. Intercrystalline corrosion was not confined to duralumin; the same kind of action occurred in other metals, and there was frequently a very striking similarity between this action and the action which accompanied season cracking, and that which could be brought about quite artificially by attacking duralumin with lead, or by attacking manganese bronze with hot solder, and he had even seen steel respond beautifully under the action of molten brass. This similarity suggested that there was a very close connection between intercrystalline corrosion and the action of cold working—excessive cold working, possibly—but he did not think that had been thoroughly proved. He had read the reports of Mr. H. S. Rawdon, referred to by Mr. Sutton, and they were particularly interesting, but the experiments dealt with were entirely laboratory experiments, and he did not think it was at all proved that the conclusions Mr. Rawdon had reached would stand the test of extended observation under manufacturing conditions. For instance, he did not think that quenching in hot water or in oil would produce the results which Mr. Rawdon had attributed to it. He did not suggest that Mr. Rawdon's observations were not right—they probably were, within the limits he had set himself in his experiments—but did not think the conclusions drawn were borne out in extended practice. So far as he himself had been able to observe, the method of quenching duralumin had not any particular effect on the susceptibility or otherwise of the material to intercrystalline corrosion. The same remarks applied to the cold work hypothesis. In so far as duralumin manufactured in the British Empire was concerned, he was prepared to say that no duralumin had ever been despatched from the manufacturers without having been cold worked after heat treatment to a greater or lesser degree, and the results of observations suggested that it would be foolish to run away with the idea that cold working was always a cause of intercrystalline corrosion. When the deformation was extremely severe, then intercrystalline corrosion might possibly arise, but one would expect that under those circumstances the ordinary surface corrosion would also be accelerated. In the same

way, annealed duralumin was very much more susceptible to ordinary surface corrosion than was a material which had been subjected to the ordinary hardening and ageing process, as shown by Mr. Rawdon. In his own view the importance of intercrystalline corrosion was, generally speaking, extremely exaggerated. Mr. Harry Brearley had once said that one could learn more metallurgy from a scrap heap than from all the universities in the British Isles. He (Dr. Aitchison) did not subscribe to that view in its entirety, but there was possibly a germ of truth in it from the angle from which Mr. Brierley was looking at the matter. He (Dr. Aitchison) had necessarily to make very close examinations of scrap heaps of duralumin, containing material which had been lying about as scrap sometimes for very long periods, and from all kinds of sources, including derelict airships, and the number of cases of intercrystalline corrosion which he had observed in such material was extraordinarily small. He emphasised that very strongly, because it appeared that Mr. Sutton had tried to make his hearers' flesh creep. Finally, he said that Mr. Sutton had given the impression that discontinuities—which he believed were now becoming more or less of only historical interest—were the result of streaks of oxide and foreign material in the metal. He did not wish to weary the meeting with an exposition of the contrary view, but he would like the opportunity to prove it to Mr. Sutton in the near future.

Mr. R. A. Parkes (Messrs. Metallisation, Ltd., Dudley): In connection with the metal-spraying process, Mr. Sutton's reference to it, and, indeed, to all processes of coating for the purpose of affording protection, was very brief. This was rather surprising, in view of the fact that the metal-spraying process in particular was capable of overcoming quite a number of the difficulties which he had mentioned as having arisen in his experiments.

The intercrystalline corrosion of duralumin was probably due to the composition of the minute quantity of material at the crystal boundaries, the various hard constituents or impurities which were thrown out of solution in the cooling of the duralumin after casting. Apart from the possibility of porosity in these hard constituents, a difference of potential between these layers and the surrounding crystals was set up at the surface when the latter became moistened with an electrolyte. Mr. Sutton had mentioned that polishing decreased the liability to corrosion in duralumin, and Mr. Parkes suggested that this was due to the fact that, in polishing, the material at the crystal boundaries became covered over with the material of the crystals due to the well-known " flow " of the metal at the surface. The heat treatment and working of the duralumin naturally governed the amount of this hard material which collected together, and, as had been found by Mr. Sutton, had a distinct bearing on the corrodibility of the finished material.

Tests which had been carried out at the United States Bureau of Standards, however, had shown that the trouble could not be overcome entirely by heat treatment or polishing. The report of the Bureau stated, in reference to paints, that " Few coatings of the paint and varnish type are completely impervious to moisture, and most of them tend to crack or blister with age, thus losing their adhesion and some of their protective power." It would appear, therefore, that if these media were employed, frequent repainting would be necessary. The report went on to say that duralumin coated with an unalloyed layer of aluminium by spraying proved superior to that protected in other ways, because the sprayed coating would stand more scratching without laying bare the duralumin. Specimens thus coated were stated to have been exposed to salt air for a year without deterioration.

From his own experience a zinc coating was to be preferred, since the surface of this would be attacked much more slowly in salt air than would a coating of aluminium, and it would at the same time give equal protection against intercrystalline attack.

Mr. Sutton's main objection to sprayed coatings was their weight, but this hardly applied to aluminium coatings as described above. With regard to coatings of zinc and cadmium, Mr. Parkes agreed that the film, to be fully protective, must be at least 0.003in. thick, corresponding to an increase of weight of about 2½oz. per sq. ft. That would not be allowed by the Air Ministry. Given a fully protective coating, however, it would be possible to use lighter alloys, for instance magnesium alloys, as the basis material. Up to now these materials had been used very little, on account of their poor resistance to corrosion.

With regard to the use of electro deposited coatings, he asked Mr. Sutton what degree of adherence he had been able to obtain. The plating of aluminium with zinc could be carried out on sand-blasted surfaces, but it was usually found that the slightest damage to the coating resulted in peeling.

The difficulty arising from intense corrosion in the proximity of copper bolts, soldered seams, etc., could be overcome entirely by spraying, since the coating was applied after all riveting and bolting up was complete.

Mr. Ulick R. Evans: Although he might be in the minority, he for one was very glad that Mr. Sutton, having set out to give a lecture on corrosion, had talked about corroded metals, and had shown his very beautiful pictures of corroded materials instead of pictures of bright and shiny parts which had suffered no corrosion. He gathered some of the previous speakers would have preferred the latter course, but it would not have been very interesting, however gratifying it might have been to the people who manufactured the said bright and shiny parts, or the material used in making them. His only quarrel with Mr. Sutton was that he had tended to hide his light under a bushel, for he had made no reference to the fact that it was he (Mr. Sutton) who had first proved quite definitely that the resistance of aluminium to corrosion was due to an oxide film, and that he had isolated this film in quite large pieces and had studied it in detail.

Reference had been made in the paper to the corrosion set up in light alloys by chlorides. Recent research, not merely on aluminium, but on other metals, had shown that there were two quite separate reasons for that. The first was that chlorine iõns appeared to be capable of penetrating weak places in the oxide film, whereas the more bulky or less mobile ions could not pierce the film. Secondly, the chlorides of most metals, and particularly the chloride of aluminium, were hygroscopic bodies, and consequently, when once a light alloy had commenced to corrode through the action of sea water, the corroded places were likely to remain perceptibly damp, even on dry days, when otherwise the surface would have dried up; thus the corrosion, once started, would continue apace. Reference had also been made in the paper to the fact that inclusions set up and promoted corrosion. That, he believed, was at least partly due to the fact that the weakest places in any protective film were likely to occur at the points where it passed from one phase to another. There might be another important reason, however—namely, that the inclusions were very likely to be surrounded to some extent by microscopic cavities. That had been suggested in the case of iron and steel by Professor Benedicks, of Stockholm, who had pointed out that when steel containing inclusions was rolled out, the "stiffness" of the inclusions was different from that of the surrounding metal, and cavities might be produced as a result. These cavities would promote corrosion, partly on account of the differential aeration effect to which Mr. Sutton had referred, and partly also because they would collect moisture, which would remain there after the rest of the surface of the metal had become dry.

The recent work of McAdam on corrosion fatigue was very important, and it had shown quite clearly that the alternating stress range was reduced if corrosive agencies were present, or, to put it in another way, that alternating stresses aided corrosive influences. Probably simply fluctuating stresses would

act in the same way, and one could suggest reasons for that. Undoubtedly the alternating or fluctuating stresses would crack the film more rapidly than it could be repaired, and also they would probably prevent the clogging of the crevices with the corrosion-product, which product would otherwise, in certain cases at least, bring the corrosion to a standstill. Meanwhile, the expansion caused by the conversion of metal into hydroxide—the aluminium hydroxide usually occupied a greater volume than the aluminium from which it was formed—produced internal stresses which aided the externally applied stresses. This combination of corrosive conditions and fluctuating stresses must operate in aeroplanes, especially seaplanes, and one could not help feeling that, in the case of many accidents attributed merely to mechanical failures, the mechanical breakage might have been rendered possible by the combination of corrosive conditions and fluctuating stresses, and would not have occurred if corrosive influences had not been present.

The difficulty of finding a suitable solder for aluminium, referred to by Mr. Sutton, was not surprising, seeing that the resistance of aluminium to corrosion was due to a protective film, and that the junction of different phases was always liable to prove a weak place in any protective film. Apart from that, however, it seemed to him that the soldering of aluminium had not really been given a fair chance. The majority of special solders which had been recommended for aluminium, at any rate in the technical press, were anodic to aluminium itself, whereas theory had indicated that it was better to have the solder cathodic to aluminium. He believed that the solders actually used at the works, as opposed to those recommended in the press, were in some cases cathodic, but he was not sure. As he had pointed out a few years ago, from the point of view of the "corrosionist," ordinary lead-tin solder was less objectionable than most of the special solders. Unfortunately, however, it possessed the very serious drawback that it did not "stick." He could not help feeling that the ideal aluminium solder, if it were evolved in the future, would probably be mildly cathodic to aluminium, but of course it must be a material which would adhere to aluminium.

Colonel N. T. Belaiew: Referring to intercrystalline corrosion, he pointed out that all Mr. Sutton's statements in regard to that phenomenon were qualified. Mr. Sutton had stated, for instance, that "In certain cases, notably in samples exposed to the atmosphere over long periods, intercrystalline corrosion occurs, but there is no corrosion at the surface apparent to the unaided eye." All that Mr. Sutton had meant, presumably, was that the corrosion at the surface was not sufficient to be seen by the naked eye, and he had not intended to convey that if the samples were examined under other conditions one would not see the channels through which the corrosive element reached the boundaries of the grains.

In future work on the prevention of corrosion in non-ferrous metals one might be guided by experience with ferrous metals. The question of protecting non-ferrous metals by oxidising was very important, and in this connection it should be borne in mind that sheets of iron were protected by scales produced during forging and similar operations. Therefore, if one had to choose between protection by oxidation and by the use of paints, it was a question worthy of very serious consideration whether it would not be advisable to direct more attention to oxidation. Finally, he suggested that the coming generation of non-ferrous metallurgists might make a valuable contribution to progress, particularly in connection with aircraft, by trying to find alloys which in themselves were non-corrodible.

Mr. Lowe-Wylde: He was glad that so many speakers in the discussion were optimistic concerning corrosion trouble, particularly Dr. Aitchison, who had taken up the cudgels on behalf of duralumin. From the point of view of those who were building aircraft in this country as a commercial proposition

the methods adopted here for protecting aluminium alloys from corrosion gave rise to much delay and annoyance. It was annoying to build a large hull, then have to take it to pieces for anodising, then re-assemble it again; the labour costs were increased, and thus the total price of a machine was increased, which made it all the more difficult to find markets abroad. He had noticed that in some places on the Continent protection against corrosion was afforded almost exclusively by the application of a sort of rubbery medium, which had elastic properties. It was very difficult to break the film of this medium, even if one bent the duralumin double, and the film could of course be applied very cheaply. The practice was to build the structure, then apply the medium, and have done with it. He had seen the Graf Zeppelin at Friedrichshafen recently, and its structure was almost entirely covered with this medium. With regard to the effect of cold working, he said that tests carried out by his company seemed to prove that cold working increased the rate of corrosion considerably. The tests consisted of immersing the objects in the river for a month, exposing them to the effects of the rise and fall of the tide; and it was found that the rivet head which had been formed, then normalised, had remained almost intact, whereas the cold-worked snap heads had almost entirely disappeared. That was very disturbing. He believed that 400 or 500 rivets had been replaced in the hull of each of the flying boats at present on the Far East flight, and that seemed to be due entirely to the increased rate of corrosion of the cold-worked portion. Finally, he asked Mr. Sutton if he had investigated the light alloy "alferium," which was used considerably in France. Chemically, he believed, it was almost similar to duralumin, but the makers claimed that it was much less liable to corrosion.

Mr. LANGLEY: Referring to the cold working of rivet heads, and the statement that this rendered them more liable to corrosion than the surrounding structure, he said that the point was that the heads were not protected by the anodic treatment applied to the remainder of the structure, so that it was necessary to fall back on the older method of applying paint and varnish to what were probably the greatest danger points. That seemed to be the great disadvantage in the use of the process, which—moreover—in his opinion, was expensive, and disorganised the programme of erection.

With regard to the rubbery medium which had been mentioned as affording protection against corrosion, he said that it also afforded protection against barnacles so that something of the sort might be particularly useful for flying boats. It has been the practice in the Mercantile Marine (he believed) to apply an anti-fouling composition with a rubber base, over the whole of the bottoms of ships, in order to prevent the attachment of barnacles, so that the development of that sort of medium might be of great value.

Dr. W. H. J. VERNON: He thought that the oxide film which formed on aluminium under ordinary conditions was of very great interest, because it was responsible for whatever corrosion-resisting properties aluminium had to its credit. That point should be borne in mind, because it placed aluminium in quite a different category from that of metals such as copper or brass. All metallurgists were familiar with the anodic oxidation process of Bengough and Stuart, whereby the thickness of the film could be increased many times, and also with the pioneer work of Mr. Sutton, who had developed the process on a large scale, and who, moreover, had demonstrated the actual thickness of the anodic film. With regard to duralumin, he considered that Mr. Sutton's micrographs had shown conclusively that the alloy was prone to intercrystalline corrosion. It was interesting to recall that in the early days of duralumin, freedom from intercrystalline corrosion was claimed as one of the advantages of the material. Those exaggerated claims had probably done more harm than good, and it was by facing the facts frankly, as Mr. Sutton had done, that real progress would be made. The paper was opportune, in view of the many new alloys

that were being exploited at the present time, particularly on the Continent, for which a high resistance to corrosion was claimed. He asked for Mr. Sutton's opinion with regard to them, and particularly with regard to alloys containing small quantities of materials such as antimony, which alloys were claimed to be very much superior to duralumin. There was a reference in the paper to the erosion of airscrew blades by impact with sea water. Mr. Sutton had made it clear that the example quoted was most probably an example of true mechanical erosion of metal. Many cases, however, formerly attributed to mechanical erosion of metal, must really be regarded (as Bengough and May had shown) as erosion of corrosion product, the primary and essential action being a chemical attack upon the metal. Cases of true mechanical erosion (of metal by liquid) were probably rare.

Commenting on the statement that opaque coatings were more protective than the transparent, and that laboratory experiments had shown that the corrosion of aluminium alloys was acceleraed by light, he asked if Mr. Sutton would place on record his experimental details, because many observations had been made from time to time on the influence of light on corrosion, and in many cases there had been more than a suspicion that some of the effects were temperature effects and not light effects. With regard to the warning not to allow a coating of enamel to become too thick, he said it was interesting to remember that for a long time it was considered that two coats of paint were less efficient under sub-aqueous conditions than one coat. More recent work of Friend had shown that it was all a question of the drying; a thinner coat probably had a better drying than a thicker coating, and as a result was more efficient; but, given suitable drying conditions and surface condition, the thicker coat was the more efficacious. With regard to the influence of protective coatings on corrosion fatigue, he said that Speller and his co-workers in America had recently found that sodium dichromate, if used in sufficient quantity to prevent corrosion, would also prevent the reduction of the air fatigue limit. Also, they had found that if a protective coating were localised, as, for example, by using painted bands, the local coating determined the point of failure by corrosion fatigue. That seemed to be very important, and indicated that if protective coatings were used to increase the fatigue limit, care should be taken to ensure that they were continuous.

Dr. BENGOUGH (*communicated*): Mr. Sutton dealt with the corrosion of aluminium in contact with other metals, *e.g.*, copper alloys and steel, and pointed out that non-corrosive steels "appear to be capable of successful use in contact with aluminium and aluminium alloys." He (Dr. Bengough) and Mr. Stuart had found that when such alloys were riveted together and tested in sea water, corrosion often occurred in the crevice between the separate pieces of metal. It would appear that a similar type of corrosion might be expected to occur where aluminium alloys were riveted to other metals, even where—as is apparently the case with stainless steels—the corrosion was not accelerated by the potential difference of the separate metals. Suitable crevices at the junction of the two metals would set up corrosion, especially under immersed conditions, due to the very restricted access of oxygen to the interior of the crevice.

Mr. Sutton attributes the pitting on the leading edge of duralumin airscrews to erosion of the metal by impact with sea water. As such airscrews generally rotate at a high velocity, the pitting may be due to actual erosion of metal in this case, but it may be noted that what appears to be erosion of metal may be due to erosion of a scale of corrosion product formed on the metal. The scale may be continually removed as it is formed. In an experiment by Mr. May, the erosion of a piece of copper strip by a jet of water was shown to be of this type, since a strip of gold was practically unchanged when exposed to similar conditions. (*Journal Inst. of Metals*, 1924 (2), p. 135.)

Mr. Sutton refers to the difficulty of protecting magnesium against corrosion. Boyer (Report No. 248, National Advisory Committee for Aeronautics (U.S.) 1926) points out that whereas the corrosion of iron and steel in neutral solution depends on the diffusion of oxygen to the metal surface, magnesium can corrode in salt solution by displacing hydrogen as gas. Hence, magnesium can corrode much more rapidly than a metal which depends on the relatively slow diffusion of oxygen. Boyer states that pure magnesium is quite resistant to corrosion by salt water, and concludes that the effects of some impurities (*e.g.*, aluminium) in increasing the rate of corrosion are due to their lowering the overvoltage of the magnesium.

In experimenting on measuring the rate of corrosion of zinc by an oxygen absorption method (Bengough, Stuart and Lee, Proc. Roy. Soc., 1927 and 1928) it has been found that purified zinc (approx. 99.99 per cent. Zn) corroding in *N*/10,000 potassium chloride solution in an oxygen atmosphere gave off an appreciable amount of hydrogen. "Spectroscopically" pure zinc under similar conditions was corroded to practically the same extent, but no hydrogen evolution could be detected. It would be interesting to know the effect on the corrosion of magnesium of extreme purification of the metal.

Mr. J. D. North (*communicated*): The anodic oxidation treatment of Bengough and Stuart, in the full-scale development of which Mr. Sutton has played an important part, has greatly assisted the use in aircraft construction of aluminium alloys which before this treatment was available were undoubtedly open to suspicion on grounds of corrosion. The treatment is also advantageous in showing up latent defects in the material anodised.

In aluminium casting alloys one's own experience is that fully modified aluminium silicon alloys without treatment or protection compare favourably with anodised duralumin or alumin in resistance to corrosion (salt spray).

Although wrought magnesium has not yet reached a stage where it can be economically employed for aircraft construction, castings of magnesium with manganese added are, in the experience of the writer, quite satisfactory; the castings are exceptionally sound, the mechanical properties are specifically very much better than any aluminium alloys, and the combination of a modified form of the dipping process to which Mr. Sutton refers on page 16 with cellulose enamel coating enables castings to stand up at least a year on the salt spray without attack.

In connection with the discussion of the question of magnesium, it is surprising that Mr. Sutton has not commented on the paper by Mr. J. A. Boyd, the Chief Chemist of the Magnesium Corporation, which has been published in Report No. 248 and the 1926 Report of the National Advisory Committee for Aeronautics, U.S.A., particularly his suggestion that polarisation is the controlling factor in galvanic action rather than differences in solution potential.

Dr. A. G. Odgers (*communicated*): *Anodic Oxidation.*—(1) The process on a works scale has been considerably cheapened by the discovery that commercial chromic acid, known in the trade as 98/99 per cent. CrO_3, may be substituted for the acid of high chemical purity, at first thought to be indispensable, without detriment to the work, the film or the life of the bath. The principal impurity is sulphuric acid.

(2) The limited life of a still costly bath is a matter worthy of fuller investigation. It has been found that a bath capable of treating 50 square feet of duralumin at a charge packs up after 700 charges or 35,000 square feet. This, notwithstanding that additions of new chromic acid are made to maintain the concentration of CrO_3 in the bath in the range 3.0—3.5 per cent. The explanation that the "valve action" ceases for some reason is not very satisfying. It is suggested that what happens may be due to the accumulation of colloidal hydroxides of aluminium and iron in the bath, and that filtration employing say

activated carbon or silica gel may remove these colloids and restore the bath to a further period of active life.

(3) It has been found that the operation of the process of anodic oxidation is of priceless value as an aid to inspection. Regions of materal defect or segregaton or unsoundness, due to any cause, are selectively attacked in the bath and rendered unmistakably visible.

Electro Plating.—Processes of the "Sherardising" class are preferred by the writer to electro plating for utilising zinc as a protective coating because of the apparently greater certainty of obtaining a non-porous coating. There appears to be no reason why such processes should not be extended to the alloys of aluminium.

Z.D. Process.—One believes that an aqueous solution of sodium silicate seals a porous casting in aluminium alloy by filling the pores with corrosion products and that there is no reason why the action should cease when the pores are filled.

Magnesium.—(1) One is glad to see the statement published that sound castings are being produced in magnesium alloys. In this respect it has been found that the magnesium castings are superior to castings in the common aluminium alloys.

(2) It has been possible to obtain satisfactory resistance to corrosion of magnesium castings by the combined treatment of chromating followed by a cellulose lacquer. Two samples are sent which have been submitted to spray from North Sea water twice daily for twelve months:—

(*a*) One half of a casting chromated only. This has corroded badly.

(*b*) The other half chromated and cellulose lacquered. This has stood up astonishingly well.

Mr. E. F. Spanner (*communicated*): This paper appears to afford further evidence that duralumin is an entirely unsuitable material for use in rigid airships. So far as R.100 is concerned, the facts disclosed do the reverse of reassuring one that the miles of duralumin strip used in making the tubes used in her construction are certain to be free from defect. Internally these tubes are screened from inspection. Externally they are exposed to chafing and continual deposits of moisture, certain on occasions to be laden with salts.

As for R.101, one would be glad if particulars could be given as to the manner in which the anodic process is applied to the duralumin strips or sections used in conjunction with the steel in the main girders.

Major H. N. Wylie (*communicated*): The information given is comprehensive, up-to-date and practical, and possesses special value in view of the reliability of the source from which it comes.

The problem of protecting the surface of duralumin and similar alloys appears to have been satisfactorily solved for parts not exposed to mechanical injury, and the author's own work in developing the anodic treatment has contributed largely to this.

The real weakness of duralumin and kindred alloys appears to be the liability to intercrystalline corrosion.

The fact that this type of corrosion can completely destroy the strength makes it very dangerous, and the danger is increased by the difficulty of detecting it, because it may proceed without any obvious external symptom.

Since it may continue in a dry atmosphere, weak spots are liable to occur while constructions are lying in store, and such weak spots, though difficult to detect, might easily prove disastrous.

These apprehensions are not based solely on laboratory experiments, indeed they arise mainly from what has occurred in aircraft built in this country and in others built abroad.

In the case of one machine which had spent almost its entire existence in the dry atmosphere of a shed there were many points at which the duralumin

had turned into a chalk-like substance and lumps could be lifted out by hand. Not only was thin metal affected but also thick metal in main members. The corrosion which caused this loss of strength could hardly be detected by eye because the original varnish covering was still practically intact.

Though some of the metal had turned into chalk-like substance having no strength, this was a very small portion of the whole. Most of the metal was quite sound and a superficial examination might have given the impression that the machine was sound and strong.

The machine referred to is not by any means unique. In fact all duralumin seems to be liable to the same disease.

Can the danger of intercrystalline corrosion be prevented by any practicable means?

The author refers to the effect of "differential aeration." Does this affect duralumin in the same way as it affects aluminium? Can examples be given illustrating the type of practical construction which favours the occurrence of this condition?

The author refers to the corrosion fatigue test that has been developed by D. J. McAdam, jun. The corrosion fatigue limit for duralumin appears to be unaffected by previous heat treatment. Thus in the annealed state the material has the same corrosion fatigue limit as in the normal state, although the static strength is less than one half.

In view of the author's statement that in the annealed state the material is much more liable to intercrystalline corrosion, is this not evidence that this type of corrosion plays no part in Mr. McAdam's tests? If this is so, this type of test is defective, in that it fails to show up what is undoubtedly the most dangerous form of corrosion to which duralumin is prone.

Colonel L. M. Wilson (*communicated*): The difficulties of protecting magnesium alloys from salt water corrosion are noted with interest and one agrees with his view that the protection of this metal from such an attack is most likely to come from within, *i.e.*, by some form of alloying, rather than from any form of extraneous coating. There should however be no danger of corrosion under ordinary suitable conditions, as magnesium alloys, if properly refined and handled, ought to be free from any particles of slag, oxides or fluxes.

In view of the rapidly increasing production of magnesium in various parts of the world, the basic cost of magnesium should be considerably lower in the near future and its alloys correspondingly more attractive to aircraft manufacturers and engine makers.

It would therefore appear highly desirable that some official research work should be undertaken to establish magnesium alloys more resistant to salt water corrosion than those at present in use.

Flight-Lieutenant N. Comper (*communicated*): The protection of light alloys against corrosion is one of the big problems that confront those engaged with both boat and float seaplanes, and it is the experience at Felixstowe that no means has yet been devised which will guarantee freedom from corrosion.

References have been made in the discussion to the unnatural laboratory treatment given to metal specimens by regular spraying with salt water. Is this treatment unduly harsh? Unless the laboratory brand of salt water is more potent than that found in the sea there is no doubt that marine aircraft in regular and normal operation meet with conditions of greater severity than are applied in the laboratory. In addition to frequent contact with salt water spray, blows are received by impact with water and, worse still, by impact with small articles of drift wood, seaweed, and general water scum. Each hard contact may chip off paint or protective oxide films and rapid corrosion is then inevitable.

One believes one is correct in stating that little reference was made to local corrosion at riveted joints. The difficulty of getting continuous oxide films or

protective paint coverings which will adhere for any length of time has still to be overcome and until a solution is reached the sting of Mr. Sutton's remarks is surely not out of place.

Major LEDEBOER (*communicated*): It may be stated without fear of exaggeration that corrosion of metals forms one of the most urgent and serious problems confronting the aeronautical engineer and the user of marine aircraft in particular. Mr. Sutton in his paper has confined himself to the corrosion of light alloys, and wisely so, for their increasing use in aircraft construction renders their liability to corrosion a matter for urgent consideration, while of recent years considerable progress has been made in the production of stainless steel.

The effects of corrosion of metals generally are far more serious in the case of aeronautical engineering than practically any other branch of engineering, since weight reduction to the lowest possible limit consistent with strength is imperative. Metal structures and parts must therefore be strictly limited to give the required factor and there is no reserve available to provide for strength reduction due to the effects of corrosion.

Now, as Mr. Sutton has stated, it is a known fact that aluminium and its alloys are particularly liable to corrosion and it would therefore appear that their use in the construction of marine aircraft will be limited in exact proportion to the efficacy of the available means of protection.

Corrosion in this case is due mainly to the direct effects of exposure to salt water, or a salt-laden atmosphere, but corrosion due to electrolytic action by contact with other metals should not be lost sight of. Many instructive examples of this have been experienced. In one instance duralumin petrol piping was found to be completely eaten away beneath steel bonding clips; in another case, a duralumin float was found to be similarly eaten away under a brass inspection plate.

A great amount of experimental work has been done in the endeavour to discover an efficient means of protecting aluminium alloys, but hitherto these means have resolved themselves in the one method of applying an external coating of some description. The great disadvantage of this method is that such an external film, whether consisting of paint or varnish, of oxide or metal deposit is liable to be scratched off in practice and this is where practice differs from laboratory methods. A duralumin hull or float may initially receive a coating of the most effective protective known; in practice it will not be long before this is removed in parts by abrasion, with the result that the film has to be constantly inspected and renewed where necessary.

The anodic process is undoubtedly an effective one and its adoption should be encouraged in every possible way, but apart from the disadvantage already mentioned, its use for large built-up structures, such as a wing unit or a hull, is limited by the fact that the anodic film is liable to be destroyed in the process of building up, as at the riveted joints of a hull. The only remedy would be to treat the completed structure, but in the case of large units this would hardly be practicable.

In the case of a hull or float, corrosion invariably starts at the rivets, which of course are not anodically treated. It is interesting to note that in general it will be found that certain batches or lines of rivets are more seriously affected than others, which would suggest that differences in heat treatment or material are responsible. Heat treatment of the rivets, of course plays an important part in corrosion, annealed rivets being subject to much more rapid deterioration than normalised rivets. Experiments have, one believes, been carried out with a view to using stainless steel rivets in duralumin and this is a line of research that seems well worth pursuing.

Paint varies enormously as a protective medium while its efficiency largely depends on its method of application. One of the main difficulties is to secure adequate adhesion to the metal and in this respect an anodically treated surface offers a good grip. It is essential that the first coat should be applied by hand and well rubbed in; the second coat can then be sprayed on to this foundation. A single coat scheme is not effective. It is most important that the paint should be applied to an absolutely clean surface, otherwise corrosion will set in under the paint, and may have reached serious proportions before it is discovered.

Commercial lanoline diluted with white spirit and well rubbed in forms a good protection in conjunction with the anodic treatment, its one disadvantage being its sticky nature which is not very pleasant.

But whatever method of protection is adopted, the fact remains that a structure or fitting so treated must be constantly inspected and the protection renewed. This is a serious matter in the case of marine aircraft, more especially so with large flying boats. As their size increases, the tendency will be to consider them as independent units capable of operating away from a permanent base; they should therefore be capable of remaining at moorings for three or six months at a time, without being brought ashore; but before this can be safely done the discovery of an effective means of protecting light alloys is essential. Another point to be noted is the extensive use of aluminium and its alloys in the construction of aircraft instruments; when such instruments are fitted to marine aircraft such parts are subject to rapid deterioration, with the result that it may eventually be necessary to take the drastic step of eliminating aluminium from all aircraft instruments, or to destroy standardisation by making special instruments for use on marine aircraft alone.

Lastly, where reliability is the first and all-important consideration, as in the case of the engine supply system, the use of light alloys will only be permissible on marine aircraft when corrosion can be effectively prevented.

These various considerations emphatically go to show that the true solution of the problem must be sought, not so much in applying an external protective film to an otherwise readily corrodible material, as in the discovery of a light metal which by virtue of its own inherent properties is not subject to corrosion. The splendid advance made during recent years in the development of stainless steels plainly points the lesson.

Reply to the Discussion

In the first place it should be made quite clear that the paper was not written with the object of discouraging the use of light alloys in aircraft as some speakers suggested, but with the intention of describing some of the more serious corrosion problems which have been encountered in the application of light alloys and the methods which have proved most successful in overcoming them.

The difficulty of obtaining a satisfactory quantitative measurement of corrosion referred to by Mr. Pye is one which is widely recognised. In the case of wrought light alloys the penetration of the corrosion effect and the enclosure of the corrosion product within the metal renders observations of change of weight of very little value. Most forms of accelerated corrosion test which have been advanced so far for observing the corrosion-resisting properties of metals have unsatisfactory features.

The crankcase in magnesium alloy, to which Mr. Pye refers, would probably be protected by the film of oil which with increasing time tends to become thicker and more adherent. Experience so far obtained has shown that crankcases in suitable magnesium alloys are not likely to be corroded seriously.

Major Barlow has referred to methods of corrosion test and has found a marked discrepancy between results obtained in the continuous salt spray test and others obtained in seashore tests. Similar experiences have been found

and the continuous salt spray test is not a good one for corrosion testing of aircraft metals and alloys. The continuously wet conditions would be expected to favour certain types of alloy in an unnatural way. Experience seems to show that the intermittent sea-water spray test in which the samples are sprayed three times each day at intervals of approximately four hours, being suspended in the open air but protected from rain, has given results which compare most favourably with the results of practical experience of parts of marine aircraft.

Major Barlow has asked for information on the behaviour of cadmium-coated steel and anodised duralumin. So far no trouble has been observed to one's knowledge either in laboratory tests or in practical applications, nor would severe contact corrosion be expected at such junctions.

The solder mentioned by Major Barlow is one of which one has no practical experience. In view of the high percentage of silver it seems likely that its melting point would be sufficiently high for its use to produce in the aluminium or alloy softening of the same order as that caused by welding. A serious objection to many solders for aluminium is that the joints, if capable of being anodically treated, are generally not protected satisfactorily.

On the subject of storage of light alloy sheets, one agrees with Major Barlow that it is necessary to store the sheets under appropriate conditions in order to prevent corrosion occurring before they are used, and desirable, in many cases, to employ temporary protectives.

As regards the aluminium-copper-silicon alloys it was interesting to learn that Major Barlow had found them no more susceptible to intercrystalline corrosion than normal duralumin because of the absence of the laminations present in duralumin. The freedom of the alloys from magnesium and in some cases from manganese also appears to permit their production in extremely sound and clean condition. Under wet conditions, particularly marine conditions, duralumin appears more resistant to intercrystalline attack, but from Major Barlow's remarks it appears that the comparative freedom from defects of the metal of his samples or components more than compensated for any greater tendency to develop intercrystalline attack. One does not doubt that in certain applications this will be the case.

It was very interesting to have Major Barlow's remarks on the rubber-base paint, but one has no experience of the paint to which he refers. Most paints for hulls appear to become charged with moisture and to retain it almost indefinitely in joints; if the one to which Major Barlow refers is free from this objection it should prove of value. One would expect that if it is a rubber coating, exposure to light would be very detrimental.

Nickel plating undoubtedly renders duralumin capable of being soldered with tinman's solder very easily and satisfactorily, but the severe corrosion which occurs by reason of the nickel plating is a serious obstacle to its use.

As regards the use of coatings of pure aluminium or duralumin, presumably Major Barlow experiences serious pitting of the aluminium coating, and this one has observed in tests, but owing to the time taken to penetrate the aluminium coating, intercrystalline attack of the duralumin is apparently delayed. Static tensile tests showed that it was a long time before the tensile properties were affected by sea-water attack. The main objection one foresees to this form of protection lies in the comparatively low fatigue limit of pure aluminium and also the very much lower sea-water corrosion-fatigue limit which would probably cause premature failure of parts subjected to fluctuating stresses of the order normally imposed on duralumin parts.

The question of fatigue and corrosion of light alloys is being investigated, and also the influence of protective coatings on the fatigue properties. It is hoped that on some future occasion it will be possible to deal with this aspect more fully.

Mr. Wallis mentioned that in his long experience of light alloys few serious cases of corrosion had come to his notice, and his statistics on the amount of protective required and the cost of its application are of much interest. One's impression is that the conditions to which the duralumin parts of an airship are exposed are normally much less severe than those against which seaplanes and flying boats have to be protected, provided that very corrosive fireproofing agents or other corrosive preparations are not used. Although for a life of some five years, or perhaps longer, protection by means of varnish renewed periodically by experienced personnel would probably prove satisfactory, one agrees with Mr. Wallis that it is of importance to have some more permanent means of dealing with the corrosion problem. In view of the high cost of varnishing, anodic oxidation would probably prove an economy, and this does not preclude the use of cellulose or other varnishes.

It is believed that in the application of duralumin in aircraft in this country the best known conditions are normally employed. The effects of some unusual conditions have been mentioned for the purpose of interest and to draw attention to the influence of those conditions.

It is not always possible in practice to use the best conditions, *e.g.*, owing to distortion by heat treatment it is frequently impossible to use duralumin in the finally heat-treated condition, as metioned by Dr. Aitchison.

Mr. Wallis mentioned a statement by Professor Jenkin with which one's own experience is in full agreement. The practical difficulty is in judging the seriousness of corrosion of duralumin by superficial examination. In laboratory experiments the corrosion product can usually be seen and examined, but in practice detrition occurs sometimes by atmospheric influences, and may under appropriate conditions render the surface of seriously corroded duralumin so uniform in appearance as to convey an entirely false impression of the actual condition.

In the absence of atmospheric influences the types of corrosion to which duralumin is subject usually manifest themselves clearly on close inspection. Cleaning operations frequently obscure the effects of corrosion to some extent and it is obviously best to examine corroded parts before cleaning or other operation likely to disturb the condition of the surface. A great advantage of the anodic treatment and lanolin form of protection is that the condition of the surface can be readily inspected.

With reference to Dr. Aitchison's remarks, few will question the importance of avoiding, if possible, the serious effects of corrosion on light alloys, and to quote instances mentioned by Dr. Aitchison, of brass and steel also. One notes Dr. Aitchison's suggestion that comparative data should be given representing the relative behaviour of the different classes of metal, and the deterioration experiences in practice over long periods; this it is hoped to do on some future occasion.

The examples of duralumin illustrated in the paper have been obtained from aircraft and the corrosion has resulted from operating conditions during normal periods of life. The pieces were selected as examples of the types of corrosion which may occur unless suitable precautions are taken and not as indications of the stages of deterioration.

Dr. Aitchison's remarks on intercrystalline corrosion bear closely upon those of Mr. Wallis, to which a reply has already been given.

Regarding Dr. Aitchison's remarks on the question of duralumin possibly containing " the seeds of disintegration " there is evidence that this or something closely similar actually occurs to some extent. Reference is here made to the somewhat erratic corrosion of duralumin plating of seaplane hulls protected by enamel only. It has occasionally been observed that certain plates corrode in a relatively short time, during which the majority of the plates show no serious attack, and that in the light of experience the location of the sheets in

the hull cannot be responsible for the attack. This may be due to the cause mentioned in connection with the corrosion of wrought alloys of the duralumin and Y alloy type by Dr. Aitchison and Mr. Barclay in their useful work "Non-Ferrous Metals and Alloys" on p. 204, viz., "the indisputable fact that the different samples of metal do not contain the same proportions of non-metallic inclusions." Dr. Aitchison will probably agree that cases of this kind present considerable scope to the metallurgist and that any metallurgical advances which would reduce the intrinsic corrodibility of duralumin would be of even greater value than improved methods of protection.

It is very interesting to have Dr. Aitchison's remarks on Rawdon's work, and one agrees that in our present state of limited knowledge of the influence of cold work, the latter should not be put down as a cause of intercrystalline corrosion. It appears possible that recognition of cold work as an important factor may have to be faced, however.

Dr. Aitchison refers to discontinuities as of only historical interest, and although at present one does not hold the same view, it is hoped that such will be the case at some time in the future. In some cases it has been found that clean gas cavities in the ingot give rise to discontinuities in forgings in duralumin. In other cases the streaks, *e.g.*, those shown in Figs. 11 and 12, are of dark colour, and there seems little doubt, when these streaks are examined microscopically, that non-metallic solid matter is present.

Referring to Mr. Parkes' remarks, it appears that the necessity for frequent renewal when paints and other organic protectives are used on light alloys is generally recognised. Much can admittedly be achieved by the application of sprayed coatings to light alloys and other metals, and the ease with which finished parts can be sprayed is a favourable point. For general protection of metal structures in aircraft an increase in weight of 2½ozs. per sq. ft. of surface would handicap the designer very seriously, and the modification of tolerances to accommodate two coatings each 0.003in. thick at joints, screw-threads, etc., would be a grave practical difficulty.

Regarding the adhesion of electro-deposited coatings also mentioned by Mr. Parkes, provided that the aluminium or alloy has been suitably sand-blasted before plating, and plated in one of the baths appropriate to the work, zinc and cadmium coatings adhere very well. With plated sheets of aluminium having 0.0005in. thick deposits of zinc or cadmium, it is unusual for the deposit to show signs of cracking or of peeling even when very severe bends have been imposed.

On the subject of corrosion by chlorides the two reasons Mr. Ulick Evans has given appear perfectly valid and represent fairly the fundamental influences which determine the behaviour of aluminium in contact with chlorides. On corroding pieces which have dried to some extent on a fine day during exposure tests it has frequently been possible to see small globules of liquid having a marked acid reaction to litmus.

As regards the influence of inclusions exposed at the surface, it is agreed that Mr. Evans' suggestion that the weakest places in the protective film are likely to occur at the points where it passes from one phase to another. This appears to be borne out by actual experience since aluminium containing large numbers of inclusions has been found to be much less perfectly protected by anodic oxidation than sounder metal.

On the subject of corrosion fatigue, Mr. Evans suggested that many cases of failure previously attributed to mechanical influences may actually have been caused by the combined influences of stress and corrosion. As a result of the examination of a large number of failures of aircraft parts there is no doubt regarding the adverse influence of corrosion.

As regards solders one is not quite sure of the ordinary tinman's solder being ideal for aluminium from the point of view of the "corrosionist." It is

quite possible, with the aid of a soldering bit, a suitable flux and a dextrous hand, to produce reasonably strong joints in aluminium with tinman's solder.

In the intermittent sea-water spray test which is described in replying to Major Barlow, such joints only last a few days owing to the fact that the solder lifts *en bloc*. Corrosion along the interface solder-aluminium or along the diffused layer between the two, appears to spread at a very considerable speed. This may be due to the reluctance of aluminium in air to exert its true electrochemical properties and to its high susceptibility to differential aeration.

Colonel Belaiew suggests the possibility of further developments in the protection of metals by oxide film. This certainly appears to be a promising field. Dr. Vernon's work had given us food for thought on the protection of copper and other metals. The extension of studies of this kind to light alloys appears to me to offer considerable scope.

Mr. Lowe-Wylde touched upon a serious practical difficulty in hull construction, in the assembly of the parts for fitting purposes, dissembly for anodising, and subsequent assembly. It might eventually prove economical to anodise complete hulls. As regards varnishes, one does not remember having any personal experience of the particular varnish to which Mr. Lowe-Wylde refers, but investigators have at some time or other been surprised at the remarkable elasticity and adhesion of certain varnishes. Unfortunately, such varnishes are as a rule influenced adversely and rapidly by the influences of sunlight and atmospheric exposure, tropical conditions being very detrimental, so that periodical renewal is essential.

As regards Mr. Lowe-Wylde's tests of cold-worked heat-treated duralumin, the results are in agreement with one's own experiments and experience of practical applications. Has Mr. Lowe-Wylde considered the possibility of inserting the rivets and riveting at the temperature of final heat treatment? Certainly, the unfortunate effects of exposing finally heat-treated and cold-worked duralumin in contact to severe corrosive influences appear to justify special and less convenient procedure.

Mr. Lowe-Wylde mentioned "alferium," and although one has only a limited acquaintance with this alloy, one is not aware of any feature which would differentiate it from duralumin.

Mr. Langley mentioned the anti-fouling properties of the rubber-varnish referred to by Mr. Lowe-Wylde. If these prove satisfactory it is agreed that the varnish would be of great value for treatment of duralumin hulls. It is believed that certain cellulose enamels are proving of value in this respect.

Dr. Vernon referred to a new alloy containing antimony added with the object of improving corrosion-resistance. Although one has not, personally, made any tests on the alloy, the results of laboratory and field tests which led to the development of the alloy have been studied and were regarded at the time as very promising. On the other hand, this alloy appears to be an exception to the relatively large numbers of new alloys for which extravagant claims are made.

Regarding the pitting of duralumin airscrews by impact with sea-water the remarks of Dr. Vernom, Dr. Bengough and Mr. Stewart are probably correct because the anodic film has proved ineffective as a preventive in certain cases in which the blades are revolving in heavy spray more than is usually necessary. The conditions are such as might be expected to be conducive to erosion of the original scale and of any subsequently formed. The contours of the pits are well rounded and render this form of attack distinct from the normal.

Regarding the interesting remarks of Dr. Bengough and Mr. Stuart on the possible effect of the crevice occurring between stainless steel and aluminium alloy in a joint, the adverse influences of the crevice appear inevitable. It appears necessary to protect the surface of aluminium in crevices by the best available means in order to secure the best result. One has not sufficient data

to enable one to say whether the corrosion of aluminium in contact with stainless steel is affected by the potential difference or not, but at present the effects of such contacts as compared with those of aluminium and ordinary steel or copper alloys appear to be small.

Their remarks on the corrosion of magnesium and also in Boyer's paper to which they refer are very interesting. The investigation of the influence of purity on corrosion of magnesium on the lines of their valuable investigation on the corrosion of zinc would be of much interest. The gradual improvement in corrosion-resistance of magnesium observed during the last ten years, and doubtless due to improvement in methods of manufacture, is perhaps significant in this connection.

Mr. North mentioned the value of the anodic oxidation process in showing up defects in the material treated. This is an important practical point. The high resistance to corrosion shown by fully modified aluminium-silicon alloy castings is undoubtedly of practical value. With regard to the magnesium alloys the serious effect of comparatively minute imperfections in the coating of enamel such as might occur as a result of mechanical injury or naturally, cannot be overlooked.

The samples which Dr. Odgers kindly sent are of much interest. The subject of deterioration of chromic acid electrolyte in the anodic process is one of practical importance, and Dr. Odgers' suggestion of treatment with activated carbon or silica gel is a good one. As regards " sherardising " processes for light alloys, the many advantages of this type of treatment are indisputable, but in relation to their application to light alloys of the high-tensile types the influence of temperature appears a serious obstacle.

As regards the silicate-treatment of porous castings, one agrees with Dr. Odgers and believes that in certain cases serious intercrystalline corrosion of castings has resulted.

Replying to Mr. Spanner, duralumin suitably protected and handled has, in the hands of experienced constructors, proved itself a suitable material for use in rigid airships. On account of its undisputed value in revealing defects and also the comparatively long lasting properties of the coating under conditions which appear to me likely to prevail within the airships to which Mr. Spanner referred anodic oxidation appears particularly suited to the purpose of protecting the duralumin parts.

Regarding Mr. Spanner's question on R.101, no abnormal procedure in the application of the anodic process to any of the parts has been adopted.

Regarding Major Wylie's interesting communication, modern investigations on the subject of intercrystalline corrosion indicate that the development of this form of attack is very slow except under conditions which would soon produce pitting sufficient in itself to be dangerous. Further, the best of the known protective processes undoubtedly restrain both forms of attack substantially.

The instances of duralumin corrosion referred to by Major Wylie appear to concern duralumin to which the anodic process had not been applied. The point he raises on the continuance of corrosion in a relatively dry atmosphere is one of practical importance, and his experiences of corrosion of duralumin aircraft structures bear very closely upon some of the remarks made earlier in the discussion.

At present one does not know of any means by which the intrinsic tendency of duralumin to intercrystalline corrosion can be removed completely, but one believes that anodic oxidation lanoline treatment of finally heat-treated duralumin, cold worked to the minimum extent if at all after heat treatment renders the possibility of trouble from this cause very remote indeed.

The " differential aeration effect " does, it seems, operate in the corrosion of duralumin and absorbent materials such as certain dope-resisting paints, fabric, timber and other non-metallic materials within a joint or forming locally

one side of it tend to give rise to serious corrosion. So far metal to metal joints in anodised lanolined duralumin have usually shown satisfactory resistance to corrosion except where sliding parts have abraded the film.

Major Wylie referred also to Macadam's work in relation to intercrystalline corrosion. At present one cannot say whether failure of duralumin in corrosion fatigue tests occurs by an intercrystalline path entirely, but one appreciates the suggestion that if this is not the case the corrosion fatigue test is of restricted significance.

Colonel Wilson mentions the freedom of modern magnesium from inclusions of slag and oxides and in one's experience the improvement in this respect has been very striking. Alloys more resistant to corrosion by sea water than those at present available would indeed be of immense value.

Regarding spray testing, the helpful co-operation of Flight-Lieutenant Comper and his colleagues has enabled the results of laboratory tests to be compared with those obtained in practice. The intermittent sea water spray has proved to be the most satisfactory method of testing corrosion resistance of metals for use in marine aircraft at a laboratory remote from the sea.

Major Ledeboer, in his interesting communication, has dealt with some of the practical difficulties. Corrosion at clips on petrol pipes and similar joints, particularly in those parts of seaplanes which are repeatedly covered with spray, certainly presents a difficulty. From the standpoint of corrosion the material of the clip should be chosen so as to reduce the possibility of contact corrosion to a minimum, and the clip should be made in such a way as to facilitate drying out of moisture entering the joint and to form a joint of the smallest possible area. Brass is one of the worst materials for use in contact with aluminium alloys as regards contact corrosion, although in parts of instruments and certain equipment it is sometimes difficult to avoid such contacts.

The question of applying the anodic process locally is one worthy of serious consideration, although this, even if practicable, would be impossible during the long cruises of large flying boats to which Major Ledeboer referred.

Major Ledeboer mentioned erratic corrosion of duralumin rivets which he has observed. It is interesting to have his confirmation of the important effects of heat treatment and to know that he considers stainless steel rivets to be a promising line of research. On the basis of the present experience of stainless steels, one may look forward to useful developments in that direction.

As regards painting and enamelling, the question of atmospheric conditions is frequently overlooked and application of the protective during very wet weather or in cold and damp sheds has been responsible for some of the unsatisfactory results occasionally obtained. One agrees with Major Ledeboer's remarks on the importance of having a perfectly clean surface.

As regards instruments, Major Ledeboer has, it seems, taken a rather pessimistic view, and the use of very resistant alloys such as the cast aluminium-silicon alloy and the application of the anodic process to the parts may prove more satisfactory than some of the parts used hitherto. Sliding parts present a difficulty, but stainless steel bushes and inserts can be used in many cases.

As regards Major Ledeboer's closing remarks, one agrees that the discovery of a strong light alloy having an inherent resistance to corrosion comparable with that of the stainless steels would be of immense value.

On the motion of the CHAIRMAN, a hearty vote of thanks was accorded Mr. Sutton for his paper and for the discussion which it had provoked.

THE IMMEDIATE AIMS OF AERONAUTICAL RESEARCH

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For the purpose of one brief lecture it is necessary to set close boundaries. In expansive mood one might, with your permission, discuss the aim in general of aeronautical research, the bending of this Force of Nature to the Use and Convenience of Man; a subject so wide and so difficult, especially our critics would say in respect of Convenience, as to call for a series of lectures rather than this single one. The immediate aims can be dealt with more briefly, and it is that which I propose to attempt. They are, in the first place, safety in flight, and, in the second, increase in what is termed performance. No other aim of aeronautical research compares in importance with these.

Danger in flight is, I am glad to say, growing steadily less. Where it still exists it is due to one of three causes. It may be due to some failure of the aerodynamic structure, to failure of the power plant, or to failure of the human element. I propose to deal with each of these in turn and to show how the research organisation of British aeronautics is seeking to eliminate each risk; and if I seem chiefly to refer to Governmental effort it is not that I do not recognise the importance of the work in this country of the Society of British Aircraft Constructors but merely that I am necessarily better acquainted with the former than with the latter. Moreover, private organisations prefer to point with pride to achievements effected rather than to lay bare their aims at a time when success must be problematical and even doubtful. Whether I am right or wrong in this view, I propose to tell you quite frankly what we are trying to do and what we hope to achieve.

The Aerodynamic Structure

The modern aerodynamic structure has undoubtedly grown in strength and sturdiness with the passing years, and the recent introduction of "all metal" construction has led to a further jump forward in this same welcome direction. On the fortunately rare occasions, however, when failure of an aerodynamic structure does occur it may be on account of unduly high unindirectional loading, or from repeated reversed stresses of less amount. An instance of the former is the over-rapid pull out of a fast dive, when for a few intense seconds an exceedingly high centrifugal load comes on to the wings of the aircraft. As an example of rapidly reversed stress, I may take the "flutter" of airplane wings which was first discovered in certain trial designs of aircraft when flown at very high speeds—200 m.p.h. and over.

Manœuvre Stresses

Let us take first the unidirectional forces. For certain military airplane manœuvres very rapid changes of direction are required. This change of direction

is brought about by the use of the controls, and with the many different designing firms that there are in this country it is natural that there should be diversity in the chosen powerfulness of such devices. Diversities there are, moreover, in pilots and in piloting. Hence it may sometimes happen that manœuvres, normally quite safe, are carried out in such conditions or in such a way, as to produce stresses higher than those for which provision was made by the designer. Although it is true that almost any pilot can break any machine in flight if he wishes to do so, just as any pedestrian can step in the way of a fast car, in practice both pilots and pedestrians seek to avoid these occurrences. To assist the former to do so we limit the sensitiveness of the controls whilst maintaining a high load factor in the structural design. It is a simple matter in an existing airplane to measure the increase of the loading due to rapid manœuvre. An ordinary accelerometer set for vertical reading, when the aircraft is in a horizontal position, will register any additional acceleration due to centrifugal force when a rapid manœuvre is carried out. If the force is five times the weight of the airplane the instrument will give a reading of 5 units, or "5g." as it is usually written. In some attitudes of the airplane, gravity will increase the load and therefore the reading, and in others, such as inverted flight, it will decrease the force and therefore the reading. The accelerometer itself is affected in just the same way as the machine of which it forms a part and its readings are a direct measure of the load coming on to the wings no matter how complicated the manœuvre which is being carried out.

There is also the effect on the pilot. When the accelerometer records 4g. the force holding the pilot in his seat is no longer merely his normal weight, but rises to an oppressive quarter of a ton! Cases of accelerations as high as this are numerous and when such manœuvres are undertaken the pilot finds it a real effort even to lift his arm, whilst rising to a standing position is impossible. An observer can continue to stand, but he must not bend his knees. Very high accelerations, if continued for several seconds, produce remarkably interesting physiological effects on the blood circulation. According to some tests made by Lieutenant J. H. Doolittle for the American Advisory Committee for Aeronautics, it appears that whilst serious physical disorders do not result from extremely high accelerations of short duration, accelerations of the order of 4.5g., continued for any length of time, result in a complete loss of faculties; this loss of faculties is attributable to the blood being driven from the head, thus depriving the brain tissues of the necessary oxygen. To the pilot it seemed that sight was the only faculty that was lost, but the Flight Surgeons at McCook Field at Dayton, Ohio, where the tests were made, were of the opinion that sight is the last faculty to be lost under these conditions, even though the pilot may be under the impression that he retains all the others.

The centrifugal force is sometimes however a very real help, as for instance when looping. It is then the sole force tending to hold the pilot in his seat.

As I have said, an accelerometer reading of 4 units is not unusual, whilst in America there is a record, as I shall presently show, of an acceleration as high as 7.8 units having been measured on pulling quickly out of a very rapid dive. This indicates that the airplane structure used in that test was capable of withstanding a load equal to almost eight times its weight and since it did not break it must have been designed with a load factor of at least 8. Now the highest lift coefficient of which the wings are capable is that which exists when the machine is flown just stalled, and its speed then is called the stalling speed. To support a load equal to 8 times the weight must therefore have at least required a speed of two and three-quarter times the stalling speed; and it is when the speed reaches this figure that a too sudden manipulation of the controls may lead to the danger zone being entered. As the level flight speed is usually less than this it will not usually happen that any manœuvre started from that attitude

will lead to danger. When this critical speed is passed in the dive, however, care in pulling out must be taken. Prior to that moment the pilot cannot overstress the machine at whatever rate he moves his control column. Even when that moment is passed sufficiently careful handling of the control column will always ensure safety.

Tests were made by the pilot, already mentioned, to see to what extent an exceedingly sudden pull on the control stick could produce an acceleration approximating to the theoretical limiting amount. As the airplane cannot be brought to the angle of attack of maximum lift instantly, the actual acceleration will, of course, not be as great as the theoretical. In order to get a comparison between the theoretical and the actual accelerations Lieutenant Doolittle pulled an airplane out of a dive as suddenly as possible at airspeeds of from 60 to 160 m.p.h. The results are shown in the following table :—

Air Speed (true). M.P.H.	Acceleration (Experimental). g.	Acceleration (Calculated). g.
66.3	1.3	1.35
76.0	1.6	1.78
85.6	2.1	3.25
95.3	2.7	2.79
105.0	3.3	3.40
114.5	3.9	4.04
124.0	4.6	4.74
133.6	5.3	5.50
143.3	6.1	6.32
153.0	6.4 (low)	7.22
162.5	7.8	8.15

It will be seen that the calculated figures are very closely approached by those obtained during this plucky test.

It is very necessary to provide that no pilot shall reach the boundary line which separates safety from danger without being made aware that he has done so. Normally the "feel" of the "stick" is his guide, and though it would be easy to provide instruments to indicate this boundary, there is a natural disinclination on the part of almost every pilot to welcome any addition to the large number of instruments he has already to consult. Careful consideration to this problem is now being given by the research organisation of the Air Ministry.

Although I have spoken chiefly of the forces which occur when pulling out of a dive, it is well to record the measurements which have been made in this and other countries during the carrying out of other manœuvres such as : Rolling (7.2), looping (6.1), spinning (3.6), vertical bank (5.7), Immelman turn (4.4), inverted flight (−1.3), bumpy weather (2.2), heavy landing (5.2).

The figures given in brackets are the highest acceleration readings of which I am aware, but in view of the diversity of types, pilots and conditions, I should be sorry to claim it as completely exhaustive. It does, however, give some idea of the stresses expected to be produced by the several manœuvres included.

The problem of manœuvre stresses is one which needs to be continually under survey by the Air Council and its advisers since with the growing "cleanness" of airplane design, the rate at which speed is gained in a dive is steadily increasing (400 m.p.h. being in sight) with a corresponding reduction in the time available for mental adjustment on the part of the pilot.

Civil airplanes are more fortunately placed; they do not have to execute rapid manœuvres and are not therefore liable to these high stresses.

Flutter

Repeated reversed stresses may arise from the phenomenon known as "Flutter," which is caused by an unstable oscillation of wing or tailplane, more commonly the former. In its simplest form it is caused by a pendulum-like action of an aileron. Imagine a "bump" coming on to the wing tips of a fast travelling machine. The tip will rise suddenly and if the centre of gravity of the aileron is aft of the hinge there will be a tendency for the latter to drag behind this motion; this increases the camber and so increases the lift. By the time the aileron has got under weigh the wing tip has ceased rising and the aileron reaches a negative angle of incidence so reducing lift; the wing tip then descends with the aileron still lagging. This motion soon builds up to a violent oscillation of the wing and aileron, and if allowed to continue may cause the breakage of the main spar. This is merely one of the forms of oscillation which may occur; it is most simply guarded against by advancing the centre of gravity of the aileron to the hinge axis or even slightly ahead of it, but the remedy has the disadvantage of increasing somewhat the aileron weight. Flutter can occur, however, in a wing which has no aileron. In fact, flutter may arise from the combined effect of flexure of the overhanging portion of the wing, of twist of the wing, and of aileron oscillation. In this highly complicated form of motion, known as ternary flutter, the equations of motion are many and the analysis difficult. A mathematical study of it, however, has been made at the National Physical Laboratory.

Pilots who have reported the occurrence of flutter have sometimes found the control column flung violently from side to side indicating an out of phase oscillation of the two ailerons; sometimes, however, the oscillation is in phase and the control stick is no longer snatched from the pilot's grasp; in the latter case, stretch of the control wires occurs and the ailerons move under elastic constraint. This difference in the action of the control cables complicates the motion and the mathematics still further. Investigation of these various phases of flutter is being carried out by and with the advice of the Aeronautical Research Committee and numerous model experiments have been made both at Teddington and Farnborough.

As a result of this study of the theory it has been possible to formulate rules for designers which may fairly be expected to have the effect of eliminating this dangerous phenomenon, or at least of relegating it to a speed range far outside that at present attainable. One of the rules relates to the mass distribution in the aileron, as already cited, another to its extension inboard of the outer struts; another to the mass distribution and stiffness in the wing itself, particularly in the part that overhangs. New fast machines at Martlesham are carefully examined for flutter by the test pilots of the R.A.F. before they are passed for service and no tribute which I can pay to the skill and courage of these men could be too high.

Spinning

Not only are machines tested thus for flutter but each is put into long continued "spins" to both port and starboard in order to detect any tendency for it to take up that troublesome form of motion known as the "flat" spin. It is known that this type of motion is aided if not induced by an improper distribution of loading producing a gyrostatic coups which tends to hold up the nose of the airplane, this tendency being aided by the gyrostatic couple of engine and airscrew for one of the senses of rotation, but it is not easy to say what distribution of load would always guard against the flat spin. The point is under continuous examination but it remains one of the unsolved problems of the moment.

The Aero Engine

It is not often that danger in flight arises from failure of the power plant. It is in fact most remarkable that it should have been found possible to reduce the weight of the engine per horsepower from 3lb. to 2lb., and even in certain cases to 1lb. with an accompanying gain in reliability. Failures when they do occur are as often as not caused by the breakage under vibration fatigue of some small pipe line such as is difficult to guard against even by the almost perfect system of inspection now in force.

A difficult problem in aero engine design is the crankshaft. It is easily made strong enough to withstand steady forces but not easily designed to be free from resonance within the speed range; such resonance if permitted to occur is likely to lead to failure of engine or airscrew. Recent work at Cambridge and at the Royal Aircraft Establishment has, however, shown how such conditions can be foreseen and guarded against.

Danger from fire in the air has been lessened by the great attention now paid to pipe lines and by the use of the fireproof bulkhead between engine and pilot. The use of fuel of lowered inflammability depends on the success of our efforts to make use of the compression-ignition cycle. This problem is being attacked on the airship R.101, where the weights allowable are higher than they would be on airplanes, and if the attack is successful a rapid extension of the work will follow. This would also avoid the more dangerous form of fire on crash. During the recent meeting of the British Association in Glasgow a demonstration was given in which a small petrol fire was extinguished by pouring on the flames a quantity of the fuel oil intended to be used on R.101.

Stalling

I now come to the failure of the human element and what can be done to guard against it. Of all such risks the most unfortunate is that " error of judgment " which leads to the airplane being stalled when near the ground. Although no risk arises from stalling at altitude, where there is sufficient room for the requisite recovery, it is dangerous near the ground, since the least tilt of the machine sideways makes the descending wing meet the air at an increased angle of incidence, and any such increase of angle when at stalling incidence leads to a decrease of lift and therefore to a tendency for the lower wing to sink still further. Hence any drop of a wing at this point leads to a rapid roll and dive into the ground.

This critical motion has been examined very carefully by Professor B. M. Jones here in Cambridge, and some very useful experiments have been carried out under his guidance at the Duxford Aerodrome. The danger is now thoroughly realised. Efforts to provide against it have been many. Perhaps the most promising until lately was the Savage-Bramson gear for warning the pilot when the stalling point was approached. But in recent years the " auto-slot " due to Mr. Handley Page has been preferred, since it operates directly instead of through that congested medium, the pilot's body. Mr. Page found quite recently that it was possible to fit one of his well-known leading edge slots at the wing tip in such a fashion that whilst it led the slot to shut itself at normal angles of incidence, it caused it to open as the stalling angle was approached. Once the slot opened, the lift coefficient increased and the dropping wing was automatically lifted. This device is remarkably simple and amazingly effective. In the early days of this invention an opportunity was afforded me to watch it in action; it was a revelation to see the incidence indicator rise to 25 degrees and more whilst the airplane held itself at only a few hundred feet over the aerodrome in an attitude so steady as quite to dispel the nervousness which such an experiment would most assuredly have otherwise caused. Such " auto-slots " are being rapidly fitted to almost every type of machine, and

unless some still better invention is produced, are likely to become of general application. Although it is true that the path of this invention was unquestionably eased by the large amount of work previously carried out by other research workers, and published in this country and elsewhere, none the less a very real measure of credit is due to Mr. Handley Page for this simple and ingenious application of scientific knowledge equally available to him and to others. What, however, we have yet to learn is whether the action of the " auto-slot " can usefully be linked in any way with the position in which the pilot puts the ailerons. Research on this is proceeding at Farnborough and elsewhere.

Other efforts to avoid the risks due to stalling are represented by the two novel flying craft known as the pterodactyl and the autogyro. The former is a monoplane with swept-back wings and no tail. The wing tips are separately controllable and act as elevators. Rudder effect is obtained by artificially increasing the resistance on either wing. Experience has shown that this machine can be flown at far higher angles of incidence than tailed airplanes, whilst for many operational reasons the absence of the tail has great advantages. This machine is due to Captain G. T. R. Hill. Two of them have been built for the Air Ministry and have shown a very satisfactory turn of speed.

The recent long cross-country flights carried out in England, France, Belgium and Germany by Senor de la Cierva's own autogyro have made this form of aircraft familiar to many. It is a tractor machine with a self-rotating four-bladed windmill in place of the fixed wings of the ordinary airplane. The British Government has had a number of these machines built for research purposes and much work has been done with models in the wind tunnel and in free drop, besides a considerable amount of mathematical work aiming at a general theory. The several flight tests made on the Government-owned autogyros have given performance figures which agree very fairly well with the forecasts made by theory. The ordinary type of airplane is ahead on the usual flying requirements, but is astern when it comes to slow flight and vertical landing. It is too early, however, to make any assessment which could pretend to be at all final of the respective qualities of the fixed and the rotating wing; the former has reached a high state of development, the latter is in its early youth. Investigation of the properties of the autogyro has been delayed by a number of small " teething troubles," but these are, I hope, now over. The Air Ministry would find the autogyro more useful if it were fitted with some form of device for the self-starting of the rotating wing—for flying boat use, some form of self-starting would be essential. Work on this is in hand. Once such a power drive were available it would be tempting to try the effect of using it during flight, the utility of such a use being supported by theory.

A novel form of aircraft, known as the helicogyre, somewhat like an autogyro but having four small engines and airscrews fitted to each of the windmill blades, is now under construction in this country. This is an adventurous development, no doubt, but the problem is not one which could be left on one side by any research organisation earnest to survey all the prospects offered by the rotating wing machine. The helicogyre should be flying in 1929.

Airplane Performance

The aim of research in respect of performance is to produce even stronger machines, at even less weight, to provide the power required for flight from even more compact and still lighter engines, and to enable greater speeds, increased ranges, and still higher altitudes to be attained; to explore to the full, in fact, all that is possible in the search for the highest constructional efficiency. The increase in " performance " possible with modern airplanes has made a heavy draft on human endurance. This can be seen by the rapid

growth in the record length of single flights which has risen from but half a mile in the year 1907 to the following record figures:—

1909	145	miles.
1911	460	,,
1913	634	,,
1920	1,190	,,
1923	3,290	,,
1927	3,911	,,

And this record of 1927 is by no means the end of the story. With larger machines carrying relays of pilots, or even with single pilot machines fitted with automatic control, there need be no limit set by piloting endurance. The mechanism of the machine itself may be run to the utmost of its fuel capacity, and that capacity grows year by year. The shapeliness of the aircraft grows also, and this, with the increasing compactness of powerful engines, has led to a corresponding growth in the speeds attained. These are the speed records of the past:—

1906	25	m.p.h.
1909	47	,,
1911	82	,,
1913	126	,,
1920	194	,,
1922	222	,,
1924	278	,,

whilst the final figure for the year 1928 will, no doubt, prove to be the 319 m.p.h. obtained by Lieutenant Greig on the Supermarine S.5, which, if not technically a "record," is the highest speed of flight ever attained.

The altitudes achieved are of less interest to the flying public since the air temperature at 20,000 feet is usually forty degrees Centigrade below that at sea level, and at 40,000 feet some twenty degrees cooler still. But as the height of flight may be important for long range flying, it is interesting that the maximum height grew from less than 1,500 feet in 1909 to over 20,000 feet in 1913, and over 40,000 feet in 1926.

In the past the water-cooled engine has been the favoured prime mover for almost all great efforts at "record breaking," but this may not always be so. Work in the wind channel has shown a good prospect that even for machines of the highest speeds the air-cooled engine with the right kind of cylinder cowling may prove a keen rival to the older form of engine, whilst for military purposes there is hardly any comparison.

I have now laid before you, however inadequately, the immediate aims of aeronautical research. What, you may well ask, will be the ultimate effect of this widespread scientific effort upon human welfare? In April, 1925, Air Chief Marshal Trenchard spoke in Cambridge on the subject of aviation, and if the *Times* is to be trusted, said: "All the good flying could do in civil life could not balance the harm that might be done by it in war. If he had a casting vote he would say abolish the air." This was an arresting saying, and its relationship to the work I have been describing is worth our thought.

Must we, when thinking of all that flying might mean to the human race, merely echo the sad conclusion of Sancho Panza, "To her own hurt grew the wings of the ant"? Had not the human ant, long before ingenious thought brought wings, experienced the embarrassment brought by other and earlier inventions? The pioneer who first discovered fire found on the one hand a way to cook his food, but on the other a means of burning down his home. The discovery of how to work metals brought on the one hand the making of tools,

but did it not lead also to the forging of swords? Knowledge of drugs brought on the one hand the art of the healer, but on the other the devilry of the poisoner. That this double-faceted picture occurs and recurs with almost all growth of discovery can be no reflection adverse to the discoverers. Science is not the sole aspect of human life, and if research brings new knowledge to humanity, it is for humanity in the meantime to prepare itself to be wise enough to use that knowledge with a minimum of harm to itself. Otherwise we must rank Sancho Panza as an unconscious prophet, "To her own hurt grew the wings of the ant."

Flying itself may be new, but has the art of using knowledge wisely begun so recently to be studied? Has the rate of production of ideas, and their material embodiment, outstripped beyond all hope the growth of moral impulse derived from the work of ethical leaders? Whatever the answer to these questions may be, it remains to the world to which flying has come to gather, and to gather quickly, the wisdom which will guard it from the passionate use of this greater freedom.

WRIGHT ANNIVERSARY DINNER, DECEMBER 17TH, 1928

On December 17th, 1903, Mr. Orville Wright made the first flight in the history of the world in a power-driven heavier-than-air machine. On the same day two flights were made by Mr. Wilbur Wright.

The Science Museum at South Kensington has been entrusted with the care of the original Wright aeroplane in which these historic first flights were made. The Council desired, on the 25th anniversary of these flights, not only to honour the names of Wilbur and Orville Wright, but to mark their appreciation of the trust shown by their Honorary Life Member, Mr. Orville Wright, in some suitable manner. At the suggestion of the President, Colonel the Master of Sempill, it was unanimously decided to hold a dinner under the original aeroplane. Colonel Sir Henry Lyons, F.R.S., Director of the Science Museum, kindly gave his permission for the function and at once offered to aid the Society in every possible way. Invaluable assistance was received from the staff of the Science Museum.

The chair at the dinner was taken by the President (Colonel the Master of Sempill, A.F.C., A.F.R.Ae.S.) and many distinguished guests assembled to pay tribute to Orville Wright and to the memory of his brother. On the tables were models displayed by Major Villiers of the Wright aeroplane; the A. V. Roe, fitted with a 24 h.p. Antoinette engine; the Cody, 50 h.p. Antoinette aeroplane; the A. V. Roe triplane, with a 9 h.p. Jap engine; the Bleriot cross-Channel monoplane; Henri Farman's machine, on which he flew over four hours in March, 1909; and the S.5 Schneider Trophy seaplane.

The honouring of the toasts of H.M. the King, H.E. the President of the United States, and H.M. the Queen, T.R.H. the Prince of Wales and the Duke of York, Patrons of the Society, and other members of the Royal Family, was followed by an address by Mr. Griffith Brewer, who was introduced by the President.

The President read the following messages among others which had been sent and received:—

Mr. Orville Wright.

I am on the way to Kitty Hawk to visit the spot on which the first flight was made twenty-five years ago with the machine around which you are now gathered. Heartiest greetings to all members and guests assembled on this occasion.

WRIGHT.

The International Civil Aeronautics Conference at Washington.

The International Civil Aeronautics Conference of Washington greets your gathering on the twenty-fifth anniversary of the Wright Brothers' first flight.

(Hon.) WILLIAM P. MACCRACKEN, Jun.,
Asst. Sec. of Commerce for Aeronautics,
Chairman, International Aeronautics Conference.

The International Civil Aeronautics Conference assembled in Washington acknowledges you greeting on this historic occasion, the twenty-fifth anniversary of the first flight ever made by man in a power-driven heavier-than-air machine. The Conference learns with consider-

able satisfaction of the arrangements that have been made to honour that epoch-making event in Great Britain, and considers it appropriate that this ceremony should take place around the original Wright aeroplane now housed in the Science Museum in London for the benefit of visitors from all parts of the world. The Conference is very happy to be in spirit at least associated with the Royal Aeronautical Society in marking an achievement which certainly opened a new era to civilisation.

(Hon.) WILLIAM P. MACCRACKEN, Jun.,
Asst. Sec. of Commerce for Aeronautics,
Chairman, International Civil Aeronautics Conference.

The Aero Club of France.

As President of the historical Commission and Centre de Documentation of the Aero Club of France, also as an old pupil of Wilbur Wright, I associate myself warmly with the commemoration of the first flights of the Wright Brothers.

PAUL TISSANDIER.

The German Scientific Society for Air Navigation
(Wissenschaftliche Gesellschaft fur Luftfahrt).

The German Scientific Society for Air Navigation (Wissenschaftliche Gesellschaft fur Luftfahrt) begs to send sincerest congratulations from Berlin to the Royal Aeronautical Society in London on the twenty-fifth return of the day on which the Brothers Wright flew, for the first time in history, on a power-driven aeroplane—heavier than air—at Kitty Hawk, U.S.A.

They hope that the two Societies will co-operate successfully in the furtherance of the whole range of international air communications for the benefit of mankind, and recall the memory of Lilienthal, whose researches with gliders were repeatedly acknowledged by the Wright Brothers as fundamental to their own success, and who, in this neighbourhood, paid for them with his life.

SHUTTE, *President.*

Messages were also received from the Imperial Aeronautical Society of Japan, the Belgian Aero Club, the Royal Italian Aero Society, and many private individuals.

During the evening the following cable was sent to Mr. Orville Wright:—

The Royal Aeronautical Society assembled with guests in the shadow of the wings of your original aeroplane send you, the first man to fly in a power-driven aeroplane, this expression of their profound admiration of your historic achievement of 25 years ago, which has been supplemented by contribution since to the advancement of aviation which was made possible as a result of the work of yourself and your gifted brother.

THE PRESIDENT, THE MASTER OF SEMPILL.

TELEGRAM SENT TO H.M. QUEEN

The Royal Aeronautical Society assembled with guests at the Science Museum, South Kensington, to commemorate the twenty-fifth anniversary of the first flight ever made by man in an aeroplane, desire

humbly to offer an expression of their deep loyalty and devotion and do earnestly pray for the early recovery of His Majesty the King.

THE PRESIDENT, THE MASTER OF SEMPILL.

TELEGRAM RECEIVED FROM H.M. QUEEN

Am commanded to convey to you and to the members of your Society an expression of the Queen's sincere and grateful thanks for the loyal and kind message of sympathy on the King's illness and for the good wishes expressed for His Majesty's speedy recovery.

PRIVATE SECRETARY.

Mr. Griffith Brewer said:—In order to appreciate the early work of Wilbur and Orville Wright, which culminated in the invention, construction, and the flying of the first aeroplane, it is necessary to take our minds back to the end of the last century, when there was a flying problem but not yet a flying art.

Many of us here will recollect that at that time, when one wished to emphasise that something was impossible, it was common to say, "You might as well try to fly." No one quibbled at this definition of the impossible.

One day in the early nineties, when I was piloting a balloon under the tuition of the late Mr. Percival Spencer, he pointed out Baldwin's Park ahead of us in our line of flight, where Sir Hiram Maxim was building a gigantic aeroplane. In those days a balloon was always a welcome visitor, so without hesitation I opened the valve and we made a good landing in the park. Mr. House, who was in charge of the construction at that time, invited us into the shed where he showed us the machine and explained what they expected the machine to do. When Mr. Spencer and I left Baldwin's Park, we agreed that the machine was extremely interesting, but we were quite convinced in our minds that mechanical flight was still impossible.

The Wright Brothers did not become seriously interested in the problem of flight until several years after the Maxim machine had been built. They learned from the literature then available, that acknowledged leaders in science such as Sir George Cayley, the Hon. Charles Parsons and Sir Hiram Maxim, had all studied the problem, and comprised that school which believed that the best method of attaining flight was to build a power machine and then learn to fly it.

There was another group, which included Otto Lilienthal, Octave Chanute and Pilcher, who believed in learning to fly on a glider before building the power machine.

The Wrights, having learnt from the books what had been already tried, recognised that the main problem was that of equilibrium and not merely the application of power to wings which would support that power. They therefore decided to build a glider, and to fly it as a kite in a high wind, with one of the brothers on board, so as to learn to balance it.

Their first departure from book practice was the system of balancing the glider by changing the angles of wing tips, instead of by attempting to change the position of the pilot. This last method had proved fatal to Lilienthal and Pilcher.

Wilbur explained their choice of learning to fly on the machine itself, when he said that there were two ways of learning to ride a horse; one way was to mount and learn by actual practice how each motion could be met; and the other was to sit on a fence and watch the horse and figure out the best way of overcoming his jumps and kicks. The latter system, Wilbur Wright said, was the safest; but the former turned out the larger proportion of good riders.

This explains the Wrights' methods in their flying experiments. Nothing was assumed to function in any particular way until it had first been tested and proved to be true.

Their first glider had an area of 165 feet, and they took it to Kitty Hawk, where they had been told by the Weather Bureau that the strongest winds prevailed. The wings were not made to any particular formula, but to a guessed curve of 1 in 22.

At Kitty Hawk (which took these young enthusiasts two or three days to reach from Dayton, Ohio) they found that in a wind of 25 m.p.h., the machine flew at an angle of about 20°; and in order to fly the machine as a kite at small angles, they had to fly it without an operator on board and manipulate the controls by cords from the ground. They made a long series of actual measurements of lift and drift of the machine under various loads. These were probably the first full-scale measurements taken of lift and drift and revealed the first discrepancies in existing tables, the lift being far less than they had been led to expect. They assumed that the depth of curvature of 1 in 22 was insufficient, and they decided that the second glider which they intended to build in the winter at Dayton, and take to Kitty Hawk the following summer, should have the recognised Lilienthal curve of 1 in 12.

Owing to the difficulty of flying the machine as a kite with one of them on board, they took the machine to Kill Devil Hill, which rises from the flat sand to a height of more than 100 feet, and they made short glides lying full length on the lower wing in order to save head resistance. The slope of the hill was a drop of 1 in 6.

The following year they brought their second glider to Kill Devil Hill. The new machne was 308 sq. feet, and the camber of the wings was the Lilienthal curve of 1 in 12. On the first glide the machine turned downwards and landed after going only a few yards. On successive glides, the operator lay farther and farther back on the machine, until after several short glides the machine flew on an undulating glide for 300 feet. No one save the operator knew that it required all the power of the elevator to keep the machine from diving or running high up into the air and then stalling.

After several very dangerous glides of this character, they came to the conclusion that the trouble was due to the deep curvature 1 in 12, and it was suspected that this induced a reversal of the centre of pressure at small angles. To test this, they took the upper surface off the machine and attached it by two cords to its front edge. They then found that in a light wind the surface flew at a large angle; in a moderate wind it flew straight; and in a strong wind it pointed downwards. This confirmed their suspicion that the centre of pressure travelled backwards when the angle became small, and would produce diving unless sufficiently guarded against. They therefore re-braced the surfaces so as to restore the original curve of 1 in 22. With this curve they now succeeded in making a large number of glides in winds up to 27 m.p.h. They were, however, unable to fly the machine as a kite with the operator on it, owing to the poor lift, in spite of the fact that the second glider was nearly twice the area of the first.

They discovered on this second glider that the pressure was inclined forward of the perpendicular, and this confirmed Lilienthal's discovery; but the measurements for lift and drift observed by the Wrights differed greatly from those given by Lilienthal.

They also discovered that their method of lateral balance by changing the angle of the tips of the wings acted in the reverse manner when gliding to the way in which it acted when flying as a kite.

On the 18th September, 1901, Wilbur read his classic paper before the Western Society of Engineers. All their work up to that time is described in that paper with the clearness and accuracy only possible from the pen of a master scientist. So clearly is their work set out, that the paper has been used

to show that the Wrights published their invention of warping control before applying for their patent, and were therefore entitled to no reward.

Having discovered, contrary to the teaching of the books, that the centre of pressure of a curved surface travelled backwards when the surface was inclined at small angles, and that measurements and formulæ published by different investigators were contradictory, they found it necessary to test everything for themselves. Up to this time they had taken up flying mostly as a sport; now they entered upon the serious scientific side of it.

A wind tunnel was built in which they tested about 50 various shaped model surfaces at intervals of $2\frac{1}{2}°$, and they made tables of all the measured results. The third glider was constructed by calculation from these tables.

In the autumn of 1902 this third glider was taken to Kill Devil Hill, where they made nearly 1,000 gliding flights, several of which covered distances of over 600 feet.

On this machine a vertical rudder was installed, adjusted simultaneously with the warping of the wings, so that by automatically turning the rudder towards the side of the machine where the wing was at the greatest angle, the warping was made to function correctly, both when gliding and when flying as a kite.

They now returned home to Dayton and built the first power machine. They were obliged to build their own engine, because no suitable engine was available. They had also to design and make the propellers. This entailed a further series of experiments occupying several months, but it resulted in a propeller built entirely from their calculations which gave useful work of 66 per cent. for the power expended. Orville Wright has told me that their propeller research was probably one of their chief works in attaining success.

If you look at the machine, you will see instruments on it which automatically record the distance flown through the air and the time occupied in flying that distance. Each flight was methodically recorded so that the lesson learned from each test could be utilised in later tests.

The long research work on the propellers delayed the completion of the power machine, so that the Wrights arrived at Kitty Hawk very late in the season, and the first power flight did not take place until the 17th December, 1903. So confident were they of success, however, that they sent a general invitation out to people of the neighbourhood to come and see the first flights. The cold December wind prevented all but five people availing themselves of the invitation.

The machine was launched by running it on a two-wheeled trolley along a wooden rail laid upon the sand, with a man at each wing to keep the machine in balance after the engine had been started and until it got towards the end of the rail and was able to take the air; and so carefully had everything been calculated, that this machine—home-made in every detail—when it left the rail was flown by Orville Wright in perfect balance, maintaining its height above the sand and landing at the end of this first flight without smashing and in perfect order for flight again.

After they had brought it back to its starting point, Wilbur flew the machine; and then Orville made the third flight; and Wilbur made the last flight on that day. That last flight lasted for 59 seconds, covering a distance of 852 feet over the ground against a 20-mile wind. Then, as a cruel sequel to the greatest mechanical achievement ever performed by man, a gust of wind caught the machine, rolled it over and made it a wreck; so that flying again on the same machine was impossible without considerable restoration work in their laboratory at Dayton.

Those four flights were the only flights this machine ever made. The broken parts remained in the packing cases for several years until, in 1912, a flood burst

the banks of the river and swept through Dayton, doing enormous damage; and amongst other damage it covered the packing cases with water and mud and left the broken machine in a still worse state of repair.

When it was decided that the machine should come to the Science Museum, I examined the broken machine with Orville Wright in Dayton, and we discussed whether it would be better to re-erect the machine with all the original parts as a museum relic, or whether to restore the machine to its original state. He decided, and I think very wisely, to restore it; the parts renewed to be identical with the original parts. The canvas on this machine is new, but it is bought from the same store in Dayton and is of the same texture as the "Pride-of-the-West" muslin originally used. The same care in restoration has been exercised in all the parts; and the struts which have been replaced are identical with those which were broken.

And so we have the privilege of being able to view this first machine which flew; the fore-runner of the new flying art which commenced 25 years ago.

On the conclusion of Mr. Brewer's address, the toast of Mr. Orville Wright and the memory of Mr. Wilbur Wright was drunk.

The dinner was made the occasion for the presentation of the Society's awards, by the President on behalf of the Council, to those to whom they had been awarded.

R.38 Memorial Prize

The R.38 Memorial Prize was founded in memory of those lost in the disaster to R.38 on August 24th, 1921. The prize, which is of the value of twenty-five guineas, is offered annually for the best paper received by the Society on some subject of a technical nature, preference being given to papers which relate to airships.

The prize for 1927-1928 was awarded to Mr. H. Roxbee Cox, Ph.D., D.I.C., B.Sc., for his paper on "The External Forces on an Airship Structure, with Special Reference to the Requirements of Rigid Airship Design."

Sir Charles Wakefield Gold Medal

The Sir Charles Wakefield Gold Medal is awarded to the designer of any invention or apparatus tending towards safety in flying. The medal for 1927 was presented to Mr. Handley Page, C.B.E., F.R.Ae.S., for his work on the Automatic Slot.

Simms Gold Medal

The Simms Gold Medal, given by Mr. F. R. Simms, M.I.Mech.E., M.I.A.E., M.I.E.E., M.I.Ae.E., a Founder Member of the Royal Aeronautical Society, was awarded to Captain F. Entwistle, B.Sc., of the Meteorological Office, for his paper, entitled "Fog," read before the Society on December 8th, 1927, which has been adjudged "the best paper read during the year before the Society on any science allied to aeronautics, *i.e.*, Meteorology, Wireless Telegraphy, Instruments."

Taylor Gold Medal

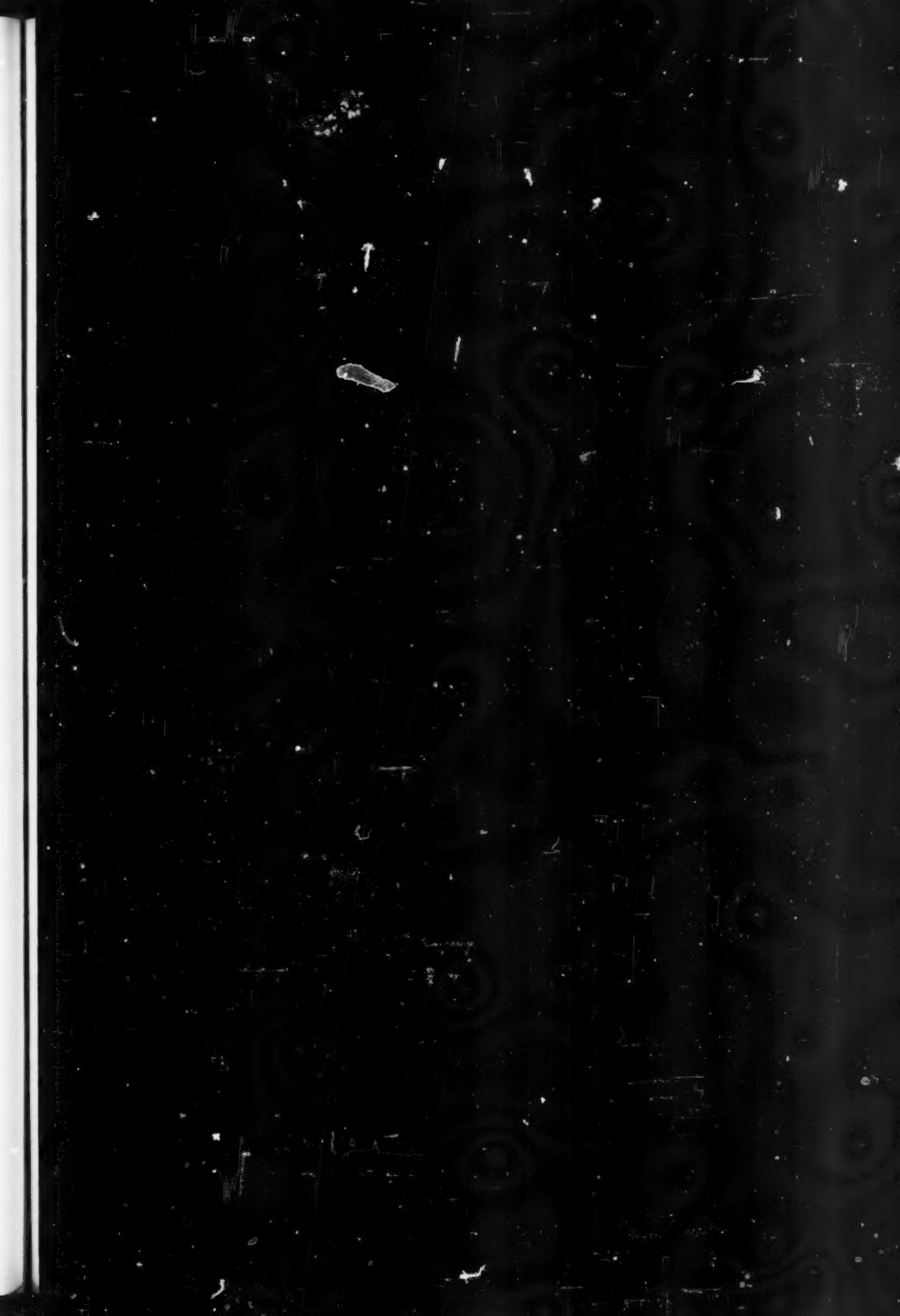
The Taylor Gold Medal, presented by Captain G. N. Taylor, was awarded to Mr. R. K. Pierson, B.Sc., F.R.Ae.S., for his paper on "The Use of the Wind Tunnel for Performance Prediction." This paper was considered to be the most valuable paper submitted and read by a member during the previous session.

Silver Medal

The Society's Silver Medal, first awarded in 1909 to S. F. Cody "for some advance in aeronautical design," was awarded for the year 1927-1928 to Mr. B. N. Wallis, for his paper on "The Design of R.100."

The proceedings closed with the toast of "The Guests," proposed by Lieut.-Colonel J. T. C. Moore-Brabazon, M.C., F.R.Ae.S., M.I.Ae.E., M.P., Vice-President of the Society, and replied to by Sir Richard Glazebrook, K.C.B., F.R.S., F.R.Ae.S., Chairman of the Aeronautical Research Committee; and the toast of "The President," by Mr. C. R. Fairey.

List of Guests

Mr. M. Atkinson Adam, B.Sc., F.I.C.
Commander A. W. S. Agar, **V.C.**, D.S.O.
Mr. Richard W. Allen, C.B.E., J.P., *President, Institution of Mech. Engineers.*
Sir Alan G. Anderson, K.B.E., *President, Institute of Marine Engineers.*
Lieut.-Commdr. M. Awaya, I.J.N.
Major B. F. S. Baden Powell, F.R.A.S., F.R.Met. Soc., Hon. F.R.Ae.S.
Mr. R. M. Balston.
Major T. M. Barlow, M.Sc., M.Inst.C.E., F.R.Ae.S.
Mr. W. E. Bartely.
Sir J. H. Biles, K.C.I.E., LL.D., D.Sc., *Hon. Vice-President, Institution of Naval Architects.*
Mr. Robt. Blackburn, F.R.Ae.S., M.I.Ae.E.
Mr. M. L. Bramson, A.C.C.I., A.F.R.Ae.S., M.I.Ae.E., *Member of Council.*
Air Vice-Marshal Sir W. Sefton Brancker, K.C.B., A.F.C., F.R.Ae.S., *President of the Institute of Transport.*
Mr. Cyril Brewer, A.F.R.Ae.S.
Mr. Griffith Brewer, F.R.Ae.S., *Member of Council.*
Mr. Mervyn Brown.
Major J. S. Buchanan, F.R.Ae.S., *Member of Council.*
Mr. H. Massac Buist, M.R.A.S., A.M.I.A.E., F.I.J., F.Z.S.
Mr. H. Burroughes, A.F.R.Ae.S.
Capt. L. W. Charley, O.B.E.
Mr. T. W. K. Clarke, A.F.R.Ae.S.
Sir Alan J. Cobham, K.B.E., A.F.C., Hon. F.R.Ae.S.
Lady Cobham.
Mr. C. G. Colebrook, Aero. Correspondent of the *Times.*
Mr. M. J. B. Davy.
Mr. F. T. Dawson.
Mons. C. Dollfus.
Lt.-Col. K. Edgcumbe, T.D., R.E. (T.), retd., *President, Institution of Electrical Engineers.*
Mr. E. C. Gordon England, A.F.R.Ae.S.
Mrs. E. C. Gordon England.
Capt. F. Entwistle, B.Sc.
Mr. C. R. Fairey, M.B.E., F.R.Ae.S., *Member of Council.*
Mrs. C. R. Fairey.
Lt.-Col. L. F. R. Fell, D.S.O., O.B.E., F.R.Ae.S.
Mrs. Fell.
Mr. H. P. Folland, M.B.E., F.R.Ae.S., M.I.Ae.E.
Mr. F. A. Foord, A.F.R.Ae.S.
Hon. Mrs. Forbes Sempill.
Mr. George Fyfe, Aero. Correspondent, *Evening Standard.*
Mr. H. Hamilton Fyfe.
Mr. H. Glaser, O.B.E., M.A., A.F.R.Ae.S.
Sir Richard T. Glazebrook, K.C.B., F.R.S., LL.D., F.R.Ae.S., *Chairman of Aeronautical Research Committee.*
The Lord Gorell, C.B.E., M.C., M.A.
Mr. C. C. Grey, Editor of *The Aeroplane.*
Brig.-Gen. P. R. C. Groves, C.B., C.M.G., D.S.O., *Hon. Sec.-Gen., Air League.*
Mr. Kohei Hama.
Major H. R. Harmon, U.S.A., *United States Army Air Attaché.*
Capt. G. de Havilland, O.B.E., A.F.C., F.R.Ae.S.
Brig.-Gen. Sir Brodie H. Henderson, K.C.M.G., G.C.B., R.E., J.P., *President, Institution of Civil Engineers.*

Air Vice-Marshal Sir John Higgins, K.C.B., K.B.E., D.S.O., A.F.C.
Mr. J. E. Hodgson, *Member of Council.*
Capt. A. G. Lamplugh, A.F.R.Ae.S., M.I.Ae.E., F.R.C.S., *Member of Council.*
Mrs. A. G. Lamplugh.
Madame de Landa, C.B.E., *Chairman, Ladies' Committee, Air League.*
Mr. D. Longden, M.I.Ae.E.
Mr. John Lord, F.R.Ae.S.
Major A. R. Low, F.R.Ae.S., *Member of Council.*
Col. Sir Henry Lyons, D.Sc., F.R.S., *Director of the Science Museum.*
Lady Lyons.
Sir Francis McClean, A.F.C., A.F.R.Ae.S.
Lady McClean.
Mr. de Witt McKenzie, *Associated Press*, America.
Lt.-Col. W. Lockwood Marsh, O.B.E., M.A., LL.B., A.F.R.Ae.S.
Air Commodore E. A. D. Masterman, C.M.G., C.B.E., C.B., A.F.C.
The Marquis Mayeda, *Military Air Attaché, Japanese Embassy.*
Major R. H. Mayo, O.B.E., M.A., F.R.Ae.S., *Representative of the Guggenheim Fund.*
Mrs. R. H. Mayo.
Mr. Gerald Merton, M.C., M.A., Ph.D., F.R.S.A.
Mrs. G. Merton.
Hon. A. F. de Moleyns.
Lt.-Col. J. T. C. Moore-Brabazon, M.C., M.P., F.R.Ae.S., M.I.Ae.E., *Vice-President of Council.*
Mr. H. H. Morris.
Mr. J. L. Nayler, M.A., A.F.R.Ae.S.
Capt. D. Nicolson, A.F.R.Ae.S.
Mr. E. Ower.
Mr. F. Handley Page, C.B.E., F.R.Ae.S., *Member of Council.*
Mrs. F. Handley Page.
Mr. George Parnall.
Lt.-Commdr. H. E. Perrin, O.B.E., *Secretary, Royal Aero Club.*
Press Association, Representative of.
Capt. J. Laurence Pritchard, Hon. F.R.Ae.S., *Secretary, Royal Aeronautical Society.*
Mr. G. Tilghman Richards, F.R.Ae.S., M.I.Ae.E.
Major F. A. de V. Robertson, V.D., M.A.
Mr. A. V. Roe, O.B.E., F.R.Ae.S., M.I.Ae.E.
Mrs. A. V. Roe.
Mr. H. Russell.
H.E. S. Saburi, *Charge d'Affaires, Japanese Embassy.*
Mr. F. St. Barbe.
Miss O. St. B. St. Barbe.
Lt. de Vaisseau A. Sala, French Air Attaché.
Mr. N. Sandberg, C.B.E.
Major T. P. Searight, A.F.R.Ae.S.
Colonel the Master of Sempill, A.F.C., A.F.R.Ae.S., *President, Royal Aeronautical Society.*
Capt. K. Shiozawa, D.S.O., *Naval Air Attaché, Japanese Embassy.*
Mr. H. O. Short, F.R.Ae.S.
Mr. F. Sigrist, M.B.E., A.F.R.Ae.S.
Mr. Stanley Spooner, Editor of *Flight.*
Mr. T. Stanhope Sprigg, Editor *Airways.*
Major Oliver Stewart, Aero. Correspondent, *Morning Post.*
Capt. R. H. Stocken, A.M.I.Ae.E.
The Dowager Lady Swaythling, *representing English-Speaking Union.*
Dr. A. P. Thurston, M.B.E., F.R.Ae.S.
Major C. C. Turner, F.R.G.S., A.F.R.Ae.S., Aero. Correspondent, *Daily Telegraph.*
Major O. G. G. Villiers, D.S.O.
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Lady Vyvyan.
Sir Charles C. Wakefield, Bart., C.B.E., LL.D., Hon. F.R.Ae.S.
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Mrs. J. G. Weir.
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Mr. R. McKinnon Wood, F.R.Ae.S., *Member of Council.*
Squadron Ldr. M. Wright, A.F.C.
Miss Wykes.